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(71) Applicant *(for all designated States except US)*: **UNIVERSITY COLLEGE LONDON** [GB/GB]; Gower Street, London, Greater London WC1E 6BT (GB).

(72) Inventor; and

(75) Inventor/Applicant *(for US only)*: **CLACK, Christopher, Donald** [GB/GB]; 31 Shakespeare Avenue, Arnos Grove, London, Greater London N11 1AY (GB).

(74) Agents: **CALDERBANK, T., Roger** et al.; Mewburn Ellis, York House, 23 Kingsway, London, Greater London WC2B 6HP (GB).

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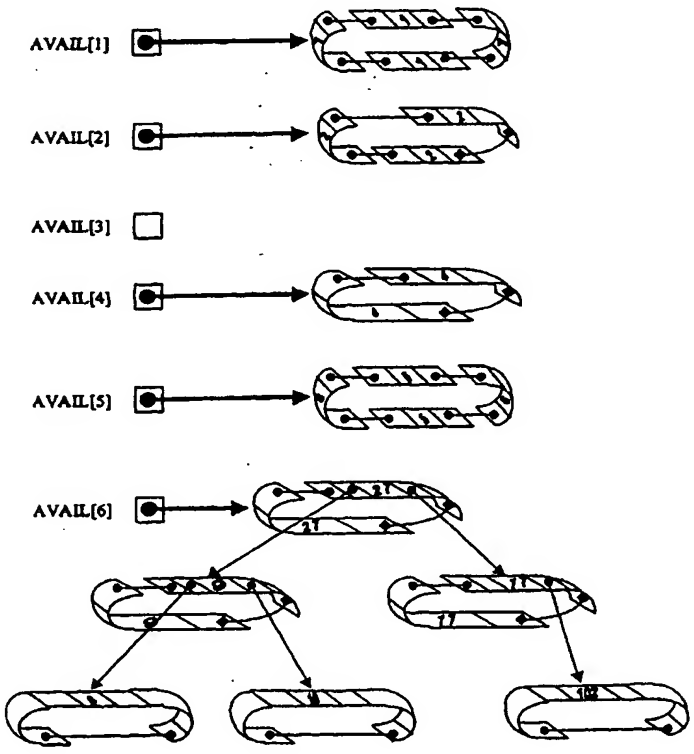
(54) Title: A DATA STRUCTURE, MEMORY ALLOCATOR AND MEMORY MANAGEMENT SYSTEM



(57) Abstract: We present a Best Fit allocator for dynamic memory management. Portions of the memory that are presently unused are call free cells, and each free cell has a size. The allocator uses a bitmap which, for each number of predetermined sizes, indicates whether free memory cells of that size exist. It also employs a second data array with an entry for each of the predetermined cell sizes. When one or more free cells of a given size exist, the corresponding entry of the data array is a pointer to one of those free cells. The free cells themselves contain pointers to other free cells of the same size, or to free cells that are slightly smaller or larger. The allocator is scalable, in that the worst-case behaviour is independent of the size of the heap, and is independent of the number of free cells and of the number of cells already in use for memory storage. It is also incremental and non-disruptive, in that each memory operation (including splitting and coalescing of free cells) is guaranteed to complete within a small bounded time. We also present a novel collector and a priority queuing mechanism that operate on principles similar to those of the allocator.

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A Data Structure, Memory Allocator and Memory Management System

Field of the invention

The present invention relates to storage of data in a *data storage space* supported by one or more *data storage devices*, and in particular to a data structure for storing data within the *data storage space*. The invention further relates to a data storage method using the data structure, to a memory freeing method using the data structure, to a data sorting method using the data structure, and to apparatus arranged to perform any of the above methods.

Background of the invention

Many of the tasks performed by modern computer systems require the storage of large quantities of data using a wide variety of *data storage devices*. In many of these tasks the total quantity of the data to be stored is not known in advance, and neither is the size of the individual packets of data which are sent for storage. Furthermore, the time for which data must be stored varies widely according to the nature of the *computational task* and the data itself.

For example, consider a computer system which is used for image enhancement. The computer system may contain a bank of original stored images of varying sizes which are held in a relatively long term storage system until it is time for one of those images to be extracted for enhancement. At that time the extracted image may be copied (or transferred) to a second memory device, and stored there for a relatively short time scale while an enhanced

version of the image is prepared. During the image enhancement procedure itself, calculation steps will be performed in which relevant data (for example Fourier data) is successively generated, stored in a third memory device, extracted from that memory device for use, and then deleted from that memory device. These operations may occur on a yet shorter time scale: for example in the time taken to process a small section of the image. The amount of data stored at any moment will vary, and may not be determined by (or even related to) the size of the original image.

Furthermore, if the image enhancement algorithm is written in a high level programming language, there will inevitably be many steps of data storage and data deletion performed by the operating system of the computer of which the user is unaware. Many of these data storage and deletion operations occur on a yet shorter time scale, and involve varying quantities of data.

With this example in mind, let us at once clarify the terminology used in this document.

The term *"computational task"* will be used here to include any computing operation performed automatically or semi-automatically by a processor (which may be a single physical unit, or alternatively a distributed processor made up of a plurality of physically separate, or even spatially distant, units). For example, *"computational task"* here includes image or sound generation or processing, processing of business or other financial data, text processing (for example, word processing or translation), etc.

The term *"data storage device"* includes any device that is capable of storing data, including devices which are internal or external to the unit including the processor. *"Data storage device"* thus includes a magnetic storage device (e.g. a hard-disk drive or floppy disk), an optical storage device (e.g. a CD storage device, such as read/write CD disk system), an electronic memory device (such as an internal or external RAM memory), and even a *data storage device* which is a portion of an integrated circuit which also carries some or all of the processor itself.

One or more *data storage devices* may together define a *"data storage space"*. For example, the external RAM memory of a conventional PC is a *data storage space*, normally supported by one or more integrated memory chips. The hard drive supports a second *data storage space*. And both of these *data storage spaces* are parts of a single *data storage space* which is the total *data storage space* of the PC.

The term *"data item"* is used herein to include any data which is intended to be stored in the *data storage space*. A *data item* may have any length (for example use of the plural word "data" does not imply that the *data item* consists of more than one bit) and any significance. For example, it may be a program (in any language), or any data to be subjected to computer processing, or which arises during computer processing.

The term *"data array"* is used to mean a section of a *data storage space* that is composed of one or more *"fields"* having a logical relationship to each other. A *"field"* may be of any *size*, corresponding to one or more *data*

items. No *size* limitation on a *field* is implied: for example, the *size* of a particular *field* may be one bit, one byte, one word, or longer. No limitation on the location of a *field* is implied: for example, a *data array* may be composed of *fields* that are contiguously located in the *data storage space,* or may be composed of *fields* that are located at discontiguous locations on different *data storage devices* in the *data storage space.* Similarly, no limitation on the location of the contents of a *field* is implied: for example, a *field* may be composed of *data items* that are contiguously located in the *data storage space,* or may be composed of *data items* that are located at discontiguous locations on different *data storage devices* in the *data storage space.* The logical relationship between the *fields* may be a linear one (for example each *field* may correspond to a respective section of a *data storage space,* and the order of the *fields* in the *data array* may correspond to the order of those sections within the *data storage space* (e.g. the order of the addresses», but any other logical relationship is also possible. For example, as discussed below in detail, the logical relationship between the *fields* may be hierarchical (e.g. the *data array* may be logically equivalent to a tree-like structure of *fields).*

Data items are either pre-existent within a *data storage space* or are stored by being written to locations within the *data storage space.* In a conventional computer system, selecting the locations for storage within the *data storage space* is one of the tasks of a unit called an *"allocator"* (which may be one or more dedicated components, or implemented in software, e.g. as one of several functions performed by a CPU). The allocator selects locations in logical units of a *"cell"*: a *"cell"*

is a data array .The *computational task* is performed by a unit called a *"mutator"* (which may be one or more dedicated components, or implemented in software, e.g. as one of several functions performed by a CPU). As the *mutator* performs its computational task, *data items* are continually being written into the *data storage space,* and deleted. Thus at any moment the *data storage space* contains *cells* which are being used by the *mutator* for storing data (such an area is known as a *"live cell"),* and *cells-which* are not being used by the *mutator* for storing data (such an area is known as a *"free cell").* A *live cell* may also become *a free cell* without any deletion of the *data items* within that *cell:* this is either achieved through express communication between the *mutator* and the *allocator* or through a process of usage analysis by a unit called the "garbage collector", or simply the *"collector"* (which may be one or more dedicated components, or implemented in software, e.g. as one of several functions performed by a CPU). A *cell* which is not live but which contains *data items* that are still useful to the *allocator* or to the *collector* is called a *"zombie cell",* or simply a *"zombie".* In general terms, data storage using *cells* is referred to as II *heap storage".* The total *size* of a *data storage space* which is available for *heap storage* will here be referred to as the quantity HEAPSIZE of that *data storage space.* The HEAPSIZE for a *data storage space* may vary during the course of the *computational-task* through the addition or deletion of sections of memory: such sections of memory are called *"chunks"* and the heap storage so implemented is called a *"chunked heap".*

For most *allocators,* a *cell* includes zero or more *fields* for the data to be stored (i.e. a

data item) and zero or more *fields* for additional data which is used for reference purposes (e.g. for the purpose of memory management itself). The latter form of data is here referred to as *"reference data"*. For example, for a one-dimensional *data storage space,* each live *cell* may store *reference data* that includes the address in the *data storage space* of one of the *fields* of the *cell.* Further *reference data* may include a *field* indicating that the *cell* is in fact live, a *field* indicating whether neighbouring *cells* in the *data storage space* are free or live, and *afield* indicating the locations of other *live cells* within the *data storage space.* For the avoidance of doubt, a *free cell* or a *zombie cell* may contain *reference data* even though it may not contain a *data item.*

We define the" *size*" of a *cell* to mean the space within it which is useable for storing a *data item.* Thus, the" *size*" of a *cell* roughly corresponds to the amount of the *data storage space* occupied by the *cell,* but the correspondence need not be exact due to the possibility of *reference data. Size* is an integer multiple of a fundamental data unit. Preferably, each *cell* will store *reference data* including the *size* of said *cell.*

When a *data item* is to be stored, how should an *allocator* search for a suitable *free cell* to store it in? One simple strategy is for the *allocator* to search through the *data storage space* (e.g. in address order) for the first *free cell* large enough to store the *data item,* and store it there. This is known as a" *First Fit*" method.

An alternative would be to search all available free *cells* and see if there is one *cell* of exactly the right *size* to store the *data item*. If there is not, the *allocator* can then search for the smallest *cell* that is large enough to store the *data item*. This is called a *"Best Fit"* criterion. In the case that the *free cell* is larger than necessary to store the *data item*, the part of the *free cell* which is not used for storing the *data item* (if it is above a predetermined *size*) may become a new *free cell*.

A further alternative is to search all available *free cells* to find the largest one, and store the *data item* there. Again, in the case that this *free cell* is larger than necessary to store the *data item*, the part of the *free cell* which is not used for storing the *data item* becomes a new *free cell*. This is called a" *Worst Fit"* selection criterion. The rationale of the " *Worst Fit"* selection criterion is that the part of the *free cell* which is not used for storing the *data item* will tend to be large, and thus" *Worst Fit"* will produce relatively large new *free cells*.

Which of the above criteria is optimal generally depends upon the *computational task* in question (e.g. the distribution of the *data items*, both in time and size, and the order of allocation and freeing of *cells)*. Preferably, a selection criterion should not lead to *"fragmentation"* (that is, the creation of a very large number of *small free cells)*. Also, preferably the time taken by the *allocator* should be *"non-disruptive"* (that is, it should never, even in a worst case, be unacceptably large) and should be *"scalable"* (that is, it should be independent of the value of HEAPSIZE).

A survey of the field of *allocators* is given in the paper "Dynamic storage allocation: a survey and critical review" by Paul R. Wilson, Mark, S. Johnstone, Michael Neely, and David Boles (in the Proceedings of the International Workshop on Memory Management, vol 986 of Lecture Notes in Computer Science, Kinross, Scotland, September 1995, Springer- Verlag). As pointed out there, the efficiency of an *allocator* in storing memory in a *data storage space* has major cost implications. Assuming, for example, that there are 100 million PCs in the world, each having 10 MBytes of memory at $30 per Byte. If just one fifth is used for heap-allocated data, and one fifth of that is unnecessarily wasted, the cost is over a billion dollars.

A further survey of the field was given by Thomas A. Standish in "Data Structure Techniques", Addison-Wesley, 1980.It is now generally accepted that *Best Fit* allocation is one of the best strategies in practice (i.e. in most cases, on real loads, compared with other general approaches such as *First Fit)* for reducing the *fragmentation* that occurs in dynamic memory management of variable-sized *cells*. For example, Shore ("On the external storage fragmentation produced by first-fit and best-fit allocation strategies", Communications of the ACM, 18(8): 433-440, August 1975) found that *Best Fit* and address-ordered *First Fit* allocation work equally well, and Wilson and Johnstone ("Real-time non-copying *garbage collection*", in Eliot Moss, Paul R. Wilson and B. Zorn, editors, OOPSLNECOOP;'93 Workshop on *Garbage collection* in Object-Oriented Systems, October 1993) present evidence that *Best Fit* is "one of the best policies" for *reducing fragmentation*.

However, it is widely believed that *Best Fit* allocation is not *scalable* because the time taken to search for the *best-fitting free cell* must always be related to HEAPSIZE. In the best case, it is assumed that the use of sorted trees can reduce the searc4ing so that it scales with the logarithm of HEAPSIZE.

A known *allocator* that uses a *Best Fit* criterion, called "Fast-fit" (described by Standish), will now be described in detail with reference to Fig. 1. This diagram shows a data structure for a memory with *free cells* of *sizes* 1,1,1,1,2,2,2,4,4,5,5,5,5,8,9,9,10,27 ,27, 77, 77 and 102. Each *free cell* contains at each end a pointer (shown in grey on the figure), pointing to another *free cell* of the same *size* (where one exists) or to the other end of itself (if no other *free cell* of the same *size* exists). Thus, the *free cells* contain enough information to define "rings" of *free cells* of the same *size*. The *allocator* also uses a *data array* AVAIL having six *fields*. AVAIL(1) is used to store the location of one of the four *free cells* of *size* 1, AVAIL(2) stores the location of a *free cell* of *size* 2. There are no *free cells* of *size* 3, and this fact is indicated in AVAIL(3). AVAIL(4) and AVAIL(5) store the location of *a free cell* of *size* 4 and 5 respectively. *Cells* above *size* 5 are treated differently. Specifically, for each ring, a representative *cell* is selected, and the representative *cells* are sorted into an AVL tree.

To store a *data item* of *size* n, the following procedure is used.

- If n less than or equal to 5, and AVAIL(n) is not empty, the *data item* is stored in *the free cell*

indicated by AVAIL(n). If AVAIL(n) is empty, we search for the smallest j (larger than n) for which AVAIL(j) is not empty. If j is less than or equal to 5, the *free cell* indicated by AVAIL(j) is split into *free cells* of *size* n and (j-n), and the *data item* is stored in the *cell* of *size* n.

- If n is greater than or equal to 6 (or in the case in the last paragraph, if no j less than or equal to 5 can be found) we use *n* as a search key to search the AVL tree pointed to by AVAIL(6), and locate a ring of *cells* whose *size* s is the smallest that is also greater than or equal to n, and if s does not equal n then split it to form two *free cells* of *size* n and (s-n). The *data item* is stored in the *free cell* of *size* n thus found or created.
- In all cases where an appropriate *free cell* is found, that *cell* is detached from its ring, with the pointers in the remaining *cells* being adjusted accordingly.
- Whenever a *cell* is split, leaving a remaining *free cell* of *size* (j-n) or (s-n), we check to see whether the neighbouring *cell* to the remaining *free cell* is free or not. If it is, we detach the neighbour from its ring and coalesce the new *free cell* with that neighbour to form a *largerfree cell*. The new *free cell* is inserted into the structure shown in Fig. 1.

The present inventor has investigated this scheme and has noticed a number of features of it. In general the time taken to identify a *free cell* for storing a *data item* rises (in the worst case) as the number of layers of the hierarchical tree. *Since free cells* may exist up

to any arbitrary *size* less than HEAPSIZE, and each ring in the tree may contain a single *cell,* and the tree has binary division, the number of layers in the worst case is of the order of log2(HEAPSIZE'/'). Thus in the worst case, the time taken for a memory storage task increases with increasing HEAPSIZE of the *data storage space.*

The present inventor has devised a variation of the Fast-fit algorithm in which it is ensured *all free cells* have a *size* less than or equal to a maximum MAXFIELDS (the *data storage space* may, for example, be generated with all *cells* less than or equal to this *size,* and coalescing of two *cells* may only be carried out in the case than a *cell* larger than MAX FIELDS is not created). In this case, the time taken for a memory storage operation is in the worst case log2 (MAXFIELDS), which is more acceptable since MAXFIELDS is not related to HEAPSIZE and may be very much smaller than the square root of HEAPSIZE.

However, this estimate assumes that the AVL tree is approximately perfectly balanced. This would not be the case, for example, in Fig. 1 if the two *cells* of *size* 77 and one *cell* of *size* 102 were used up. As the tree becomes less balanced finding *cells* of a given *size* takes longer compared to the number of rings, and in the worst case, the time taken to find a *free cell* scales with the number of rings. To ensure that this does not occur, a complex and time consuming occasional "re-balancing" algorithm would be required (re-balancing of an AVL tree is called "rotation"). While this operation is carried out, data storage is not possible, and thus the re-

balancing may cause unacceptable disruption of the *computational task.*

Any *allocator* gradually uses up the *free cells* in the *data storage space,* so, for memory storage to be sustainable, there must be a mechanism for generating new *free cells.* That is, when it is no longer required to store the data in a *live cell,* there should be a mechanism for converting the *live cell* into a *free cell* (i.e. for "freeing" *cells).*

In some systems, the freeing of memory is decided by the programmer. However, it is increasingly common for programming systems to offer automatic dynamic memory management including automatic freeing of *cells* that are no longer being used by the *mutator;* such cells are called " *garbage cells*" .This is referred to here as " *garbage collection*", or simply *"collection",* and is performed by the *collector* (as previously defined).

In the implementation of functional programming languages in particular, automatic detection and freeing of *garbage cells* is required. Preferably, *collection* should be *scalable,* and *non-disruptive.* Such *collection* overheads (which lead to short memory-management pauses due to allocation or *collection)* are vital for interactive and real-time applications.

Baker's incremental copying technique (Henry G. Baker, "List processing in real-time on a serial computer". Communications of the ACM, 21(4); 280-94, 1978) might be expected to form the natural basis for a *collector* with the required behaviour. However, the worst-case cost of

Baker's read barrier is potentially very high and very unpredictable.

Another sort of *collection* system (see G. E. Collins, "A method for overlapping and erasure of lists". Communications of the ACM, 3(12):655-657, December 1960) is known as *"reference counting"* (i.e. counting the number of *live cells* which point to a particular *cell* - for each *cell*, this is called the *"reference count"* for that *cell*). The *reference count* for each *cell* is normally held as part of the *reference data* for that *cell*. The advantages of *reference counting* are:

- it is naturally incremental (it is performed in small steps interleaved with computation);
- it is naturally distributed and can improve locality of reference.
- it is easy to implement;
- there is no root-set to be scanned (an important determinant of real-time performance);
- the overheads are predictably related to actual *mutator* activity rather than to the size of the heap or the numbers of *live cells* (many of which may be inactive for long periods);
- its behaviour does not degrade with increasing heap occupancy;
- it is decoupled to a large degree from the *mutator*; synchronisation with the *mutator* is not required, and (unlike incremental tracing *collectors*) the *collector* is not fooled by *mutator* activity -the algorithm is therefore simpler.

Consider the following three memory operations:

1. *cell* allocation (and issuing of a pointer to the *mutator)*

2. pointer copy

3. pointer deletion

Using *reference counting,* the first two of these operations may be achieved with constant-time *garbage collection* overhead. However, a complication arises after a *garbage cell* has been identified (always as the direct result of pointer deletion). If a *cell's reference count* drops to zero, it is garbage; before returning the *garbage cell* to the *allocator's* data structure for managing *free cells,* it is necessary to inspect each of this *cell's fields* and delete any pointers held therein. We call this action *'freeing" a field.* The deletion of a pointer in this way might lead to another *cell* being identified as garbage, so potentially leading to a cascade of deletions. The time taken to service a deletion cascade is unpredictable and may be large. It is therefore important that such cascades are avoided.

This problem is well-known and solutions have previously been proposed, for example by *I.* Wiezenbaum ("Symmetric list processor", Communications of the ACM, 6(9): 524-544, September 1963).

- When a *cell* is identified as garbage it is placed on a "to be collected" data structure - these are *zombie cells,* as previously defined;
- The *fields* of *zombie cells* are freed incrementally, interlaced with other *mutator* activity;
- When all *fields* in a *zombie* have been freed, the *cell* becomes free (it is passed to the *allocator).*

One option is to inspect *zombie fields* just prior to each *cell* allocation (since at this point we know that the

mutator requires more memory). If the freeing of a *zombie field* causes a pointer deletion, thereby causing another *cell's reference count* to become zero, then that *cell* simply becomes a *zombie* -the *fields* in the subsequent *cell* are not inspected and no cascade occurs. This simple procedure eliminates cascades but introduces a further tension:

- If we guarantee always to free more *zombiefields* (if they exist) than the number of *fields* required for the *cell* allocation, the *collector* always makes progress *(collection* exceeds allocation whilst there is garbage to be collected);
- If we guarantee always to free an exact number of *zombie fields* before each allocation, the *garbage collection* overhead for *cell* allocation is constant (given a fixed MAXFIELDS limit).

In a system with variable-sized *cells,* it is not possible to guarantee both that the *collector* makes progress and that the *collection* overhead per allocation is a small constant.

At the point of *cell* allocation, a *zombie* cell-should be freed. But which *zombie* should we choose?

- If we always free the largest *zombie* first, the resultant *free cell* can be used to satisfy many more allocation requests than a small *cell;*
- By contrast, Last-In-First-Out (LIFO) freeing (i.e. the most recent) encourages depth- first freeing of cascades and might lead to better cache performance;
- However, it may be preferable to coalesce older *cells* before younger *cells* using First- In-First-Out *(FIFO) freeing,* in order to improve fragmentation behaviour.

The choice of strategy affects the overheads for *cell* allocation. Both LIFO and FIFO *zombie* freeing can be achieved with constant time overhead per operation using a stack or queue, whereas largest-freeing requires that the largest *zombie* be found. This is a search comparable in nature to the search described above in relation to *free cells*, and thus exhibits the same problems of scaling and possible disruption.

Summary of the invention

The present invention seeks to address one or more of the above problems, and to provide a novel and useful data structure.

Preferably, the present invention seeks to provide a data structure that-makes possible a memory management system which is *scalable, non-disruptive,* and employs *Best Fit* allocation together with *non-disruptive* coalescing.

Preferably, the present invention makes it possible to achieve a *(chunked)* heap of variable-sized *cells* to be managed such that:

- *Fragmentation* is minimised, using *Best Fit* allocation (including cell-splitting and coalescing *offree cells).*
- The system is *scalable,* i.e. has memory-management overheads (in terms of memory accesses) being independent of the numbers *offree cells* or *live cells,* and independent of the *size* of the heap (which, with a *chunked* heap, may grow at runtime).
- Memory management is *non-disruptive* (for example, there are no "embarrassing pauses" whilst *free cells* are coalesced), and the three operations of *cell* freeing, *cell* allocation and *cell* coalescing each have a small bounded overhead in terms of memory accesses.

In a first aspect, the invention proposes in general terms that a data structure includes a first *data array* which indicates the existence of *cells* of a predetermined type (e.g. *free cells)* and of a predetermined *size,* and a second *data array* which indicates the location of such *cells* within the *data storage space.*

Specifically, in this first aspect the invention provides a data structure comprising:

- a *data storage space;*
- a first *data array* which, for each of one or more *cell sizes,* stores data indicating whether or not the *data storage space* includes at least one *cell* of a certain type and of the respective *size;* and
- a second *data array* which, for any said *size* for which at least one *cell* of the determined type exists, indicates a location of at least one *cell* of that *size* and type within the *data storage space.*

The first and second *data arrays* may each be sections (which may be allocated statically before the start of the computational task, or dynamically during the computational task, or comprise both statically-allocated and dynamically-allocated parts) of said *data storage space,* or sections of one or more additional *data storage spaces.* Though logically separate, the first and second *data arrays* may be merged to facilitate implementation. The "type" of *cells* may be *free cells,* or alternatively *live cells.* However, the term "type" is not limited in this respect. For example, a "type" of *cells* may be *cells* which, irrespective of whether they are live or free, possess some additional characteristic, such as including certain data. Preferably, the *cell* types are predetermined, but alternatively it would be possible for

them to vary (e.g. be regularly reset) as part of an optimisation of the data structure in relation to the *computational task* in which it is employed.

One type of *cell* to which the invention is applicable, for example, is *cells* which do not contain *data item(s)* that are useful to the mutator but do contain pointers (to other *cells)* which may be useful to either the collector or the allocator. For example, *zombie cells* discussed above.

In the case that the type of *cells* is *free cells* (i.e. portions of the *data storage space* which are not presently being used by the *mutator* -for storing data), when it is desired to store a data unit of a certain *size,* the first *data array* can be used to identify a suitable *cell size* for storing it (e.g. the smallest *cell size* which is at least as large as the data unit and for which at least *onefree cell* exists), and the second *data array* can be used to locate a *free cell* of that *size,* so that the data unit can be inserted into it.

Preferably, said predetermined *cell sizes* are all no more than a predetermined maximum *cell size* (MAXFIELDS), which is independent of the total *size* of the *data storage space* (HEAPSIZE). For example, said predetermined *cell sizes* may be all *cell sizes* up to the predetermined maximum *cell size.* This means that the *size* of both the first and second *data array* may depend upon MAXFIELDS but be unrelated to HEAPSIZE.

Preferably, the first *data array* may be selected so that for a *cell size* n it is possible to determine the smallest (integer) value of p such that p>n and there exists at least one *cell* of the predetermined type of *size* p, within a time which scales with log (MAXFIELDS).

Alternatively, or additionally, the first *data array* may be such that for a *cell size* n it is possible to

determine the largest (integer) value of p such that p<n and there exists at least one *cell* of the predetermined type of *size* p, within a time which scales with log (MAXFIELDS).

For example, the first *data array* may be a hierarchical *data array*, having:

- a first level which includes one or more first *fields*, each first *field* indicating for a respective *size* of *cell* the existence or otherwise of at least one *cell* of that *size*, said first *fields* being divided into one or more groups, each group representing a respective range of *cell sizes*; and
- a second level which includes one or more second *fields*, each second *field* indicating for a respective said group the existence or otherwise of at least one *cell* in the respective range of *cell sizes*.

We will refer here to the first layer as the "lowermost" layer, and to the second layer as a "higher" layer. We will use the names "layer" and "level" synonymously. We will say that a particular *cell size* is *"related"* to any *field* of the first *data array* when that *field* either (i) contains information about the existence of *cells* of that *size*, or (ii) contains information about another *field* which is itself *related* to the particular *cell size*. When for a given *cell size* there is at least one *cell* of the predetermined type having that *cell size*, we say that that *cell size* is "occupied". Similarly, when *afield* in the first *data array* indicates that one of the *cell sizes* *related* to it is occupied, we will say that that *field* is "occupied".

Preferably, the first *data array* contains further layers "above" the second layer. In each i-th layer there are one or more *fields*. Unless the i-th layer is the top

layer, the one or more *fields* are divided into one or more groups, each group representing a range of *cell sizes,* and in the (i+1)-th layer there is *a field* for each respective group of the i-th layer. Thus, any particular *cell size* is, in each layer, *related* to a single respective *field.* The existence of at least one *cell* of that particular *cell size* determines information in all *fields related* to it, in all layers of the *data array.*

If all groups contain two or more fields, at each level the number *of fields* is at most half the number of *fields* in the layer below. To be precise, if each *field* in an (i+1)-th layer represents a group *of p fields* in the i-th layer, the (i+1)-th layer contains p times as many *fields* as the i-th layer. The largest *cell size* represented by the first *data array* is MAXFIELDS, so the total number of layers scales as log p (MAXFIELDS). This has the effect that a search within it for a *cell size* which is occupied, takes a time which scales as log p (MAXFIELDS).

We will now give a single example of how this search may be carried out:

Suppose that for a given (unoccupied) *cell size* n we wish to find the lowest occupied *cell size* higher than n. To do this we begin at the lowest level of the table with the *field* related to n. We then ascend the table layer-by-layer.

- In each layer including the lowest we determine whether, in the group including the *field related* to *cell size* n, there is at least one *occupiedfield* representing *cells* larger than n.

- If so, then we select the smallest such *occupiedfield,* and move back down the layers, at each layer selecting the occupied *field* which is *related* to the selected *field* in the layer above and which represents the smallest *cells.* The *cell size* we arrive at in the lowest layer-is the one sought.
- Otherwise, we go up one layer higher.
- If we reach the top layer, we check to see whether in that top layer there is at least one occupied *field* representing *cells* larger than n.
- If so, then we select the smallest such occupied *field,* and move back down the layers, at each layer selecting the occupied *field* which is *related* to the selected *field* in the layer above and which represents the smallest *cells.* The *cell size* we reach in the lowest layer is the one sought.
- Otherwise, no such *cell* exists.

Preferably, in each layer, each group represents a number *of fields* in the layer below which is a multiple of eight (e.g. eight, sixteen or thirty-two). Occupancy or otherwise of a *field* may be represented by a binary digit. In this case, the group of *fields* may conveniently be represented as an integer number of bytes. In this case, for many computer systems, the operations required for searching the tree can be carried out significantly more quickly (in real time), because the *data array* can be simply a bitmap.

If there are *32fields* per group, then it is possible to achieve the search in a time of O(log32 (MAXFIELDS)). IfMAXFIELDS=32k, log32 (MAXFIELDS) is just 3, so the first *data array* has only three levels.

Although, as mentioned above, the predetermined *cell sizes* may be all *cell sizes* up to the value of MAXFIELDS, this is not in fact a necessary feature of the invention. A further option within the scope of the invention is to treat *cells* in different ways according to their *size*. For example, it may be the case that due to *fragmentation* there will always in practice be a large number of very small *cells*, so that the first *data array* is not needed for such *cells*. Thus, it may prove more efficient for the first *data array* only to be used for *cells* having a *size* which is at least a predetermined minimum *size* (here called "MINFIELDS"), and for *cells* smaller than MINFIELDS to be indexed differently. For example, the very small *cells* might be treated in a manner similar to the Fastfit algorithm described above. That is, for *cells* smaller than MINFIELDS, the second *data array* could contain: (i), in the case of a *cell size* for which *cells* do exist, a pointer to such a *cell*, or (ii) in the case of a *cell size* for which *cells* do not exist, data indicating that fact.

Thus, for example, in the case that the *cells* are *free cells*, and it is desired to locate a very small *free cell* (i.e. below the predetermined *size)* to store a small data unit, this could be done using the second *data array* only. Provided that MINFIELDS is a value that is unrelated to either HEAPSIZE or MAXFIELDS (that is, it does not scale with HEAPSIZE or MAXFIELDS), the time scaling of the overall algorithm may be unaffected.

The existence of MAXFIELDS is not in fact a necessary feature of the invention. A further option within the scope of the invention is to allow the first and second *data arrays* to contain *fields* for all *cell sizes* up to HEAPSIZE (which may vary). This option may be further optimised within the scope of the invention to

allow the first and second *data arrays* to contain fields for all *cell sizes* up to the largest *cell size* yet allocated at any given time during the performance of the *computational task* and for the size of the first and second *data arrays* to be modified dynamically (including extension, contraction and re-balancing as necessary) during the *computational task*.

The invention has been explained above using a first *data array* which indicates the existence or otherwise of a *cell* of an exactly predefined *size*. However, all of the above concepts are straightforwardly applicable to a case in which the *cell sizes* are in fact binned (i.e. conceptually divided into ranges), and the first *data array* is in fact used to indicate the existence of a *cell* within a certain range.

Thus, the first aspect of the invention may alternatively be expressed as providing a data structure comprising:

- a *data storage space;*
- a first *data array* which, for each of one or more *cell size* ranges, stores data indicating whether or not the *data storage space* includes at least one *cell* of a certain type within the respective *size* range; and
- a second *data array* which, for any of said *size* ranges for which at least one *cell* of the determined type exists, indicates a location of at least one of those *cells* within the *data storage space*.

In the case that the *cell size* ranges are each only one unit wide, this reduces to the expression of the first aspect of the invention given earlier. However, alternatively, any *cell size* range may be wider than one data unit (so that it includes two or more possible *cell*

sizes). The largest *cell size* range may be defined as all *cells* up to a predefined *size* (which corresponds to MAXFIELDS, or to HEAPSIZE in the option that MAXFIELDS is not used).

Preferably, the *cell size* ranges are predetermined, but alternatively it would be possible for them to vary (e.g. be regularly reset) as part of an optimisation of the data structure in relation to the *computational task* in which it is employed.

In either case, the width of a given *cell size* range may be a function of the lower limit of the *cell size* range. For example, the *cell size* range may for example be selected to be wider for higher *cell sizes,* since in that case the inefficiency caused by the coarse graining of the *cell sizes* (i.e. the waste caused by replacing an "exact-fit", by an approximate fit) is only a small fraction of the *size* of the *cell*. This is in fact a further example of the option mentioned above, of treating *cells* of different *sizes* differently.

Preferably, the *cell* types are predetermined, but alternatively it would be possible for them to vary (e.g. be regularly reset) as part of an optimisation of the data structure in relation to the *computational task* in which it is employed.

As mentioned above, all preferable features of the data structure according to the first aspect of the invention are applicable within the scope of the invention to the case in which the *cell sizes* (whether predetermined or varying) are generalised to *cell size* ranges. However, for simplicity of terminology, the following explanation is given on the basis that the *cell sizes* are predetermined as exact values (i.e. not ranges). Similarly, for simplicity of terminology, the

following explanation is given on the basis that the *cell* types are predetermined.

The data structure preferably includes *a field* which stores the location of at least one of: (i) a *cell* of the predetermined type having the greatest *size* (among the predetermined *sizes)* for which *cells* of the predetermined type exist *(this field* is herein called "MAXP"), or (ii) a *cell* of the predetermined type having the smallest *size* (among the predetermined *sizes)* for which *cells* of the predetermined type exist *(this field* is herein called "MINP").

MAXP is useful, for example, in the case that the predetermined *cell* type is *a free cell,* because it means that the *Worst Fit* method can be used for selection of a *free cell* to hold a *data item.* MAXP is also useful in the case that the predetermined *cell* type is a *zombie cell,* because in that case it is easy to find the largest *zombie cell* to free.

Furthermore, in the case that the predetermined type of *cell* is *a free cell,* if it is determined (e.g. using the first *data array)* that no *cell sizes* equal to or less than n are occupied, then MINP points to *a free cell* which (among the extant *free cells)* is of the smallest *size* capable of storing a *data item* of *size* n.

Preferably, the *cells* of the predetermined type contain pointers to (i.e. data indicating the location of) each other. A pointer is a further example *of reference data.* For example, each *cell* may contain at least two such pointers.

Preferably, pointers of the *cells* of each predetermined *size* are such that, starting from any *cell* of any predetermined *cell size,* any other *cell* of the predetermined type and the same *cell size* can be

reached by moving successively from one *cell* to another according to the pointers.

Preferably, at least one *cell* of each predetermined *size* contains a pointer to one of the *cells* of the next higher occupied predetermined *cell size*. Preferably, at least one *cell* of each predetermined *size* contains a pointer to one of the *cells* of the next lower occupied predetermined *size*. If both of these conditions are met, then it is possible to move between all *cells* of the predetermined type having any of the predetermined *sizes* using pointer information alone.

For example, in the case that the predetermined type of *cell* is a *zombie cell*, it is possible to start at the *cell* indicated by MAXP, and move through all the *zombie cells* in an order in which the *size* of the *zombie cells* never increases (i.e. only decreases or remains the same), using the pointers. This possibility may be particularly useful for *garbage collection*.

The order of the path defined by the pointers through *cells* of the same *size* may encode information about the *cells* of that *size*, for example the age of the *cells* (i.e. the time since they were created).

For example, in the case of a path towards lower *cell sizes*, the *cell* of any given *size* which is indicated (pointed at) by a *cell* of the next higher *size*, may be the oldest *cell* of the given *size*, and the *cells* along the path towards the *cell* which points to the next lower *size* may be progressively younger. This age order makes it easy to locate old (or young) *cells* of a given type and *size* (for example, for conversion to another type of *cell*). The age order may be preserved by, whenever a new *cell* of the given *size* is created, changing the pointer in the youngest *cell* of the given *size* to point at the

new *cell*, and arranging for the new *cell* to contain a pointer to a *cell* of the next lower *size*.

Clearly, the scheme of the preceding paragraph may be varied within the scope of the invention, to provide a data structure in which the path leads from young *cells* to old *cells*, and/or to the case that the path leads from small to large *cells*.

Preferably, whenever a first *cell* of the predetermined type contains a pointer to a second *cell* of the predetermined type (of the same or different *size*), that second *cell* contains a pointer to the first *cell*. This has the effect that the path may be followed in either direction (i.e. towards either larger or smaller *cells*).

Although in principle the second data array may store the location of any (or all) of the cells of the predetermined size (or size range), it is preferable that the (at least one) cell of each size (or size range) is selected according to a characteristic of the cell. For example, a further option within the scope of the invention is for the second *data array* to contain, for each *cell size* or *cell size* range, the locations of both the youngest and the oldest *cells* of the predetermined type and of the predetermined *size*. Alternatively, or additionally, the second *data array* may contain, for each *cell size* range, the locations of both the biggest and the smallest *cells* of the predetermined type and of the predetermined *size*.

A straightforward way of realising MINP is for the data structure to include at least one *cell* of the predetermined type (herein referred to as a" *sentinel cell")* which is of *size* MINSIZE or less (e.g. it might be of *size* zero) having a predetermined location in the *data storage space* and containing a pointer to a *cell* of

the predetermined type of the next higher *size*. In other words, a pointer to the *sentinel cell* thus constitutes the MINP *field*. Since the *sentinel cell* exists, a search using the first *data array* for a *cell* of the predetermined type of highest *size* lower than *size* n will find the *sentinel cell* if no *cell* of intermediate *size* exists, and the pointer in the *sentinel cell* leads to a *cell* of the minimum *size* greater than n.

In principle, a *sentinel cell* with *size* MAXFIELDS and a predetermined location could additionally, or alternatively, be provided in the data storage structure.

A further option within the scope of the invention is for either the MAXP field or the MINP field or both fields to be contained in the second data array.

In fact, the concept of using pointers as described above constitutes an independent second aspect of the invention.

Specifically, in the second aspect the invention proposes a data structure including:

- a *data storage space*, the *data storage space* comprising one or more *cells* of a certain type, each said *cell* of said type containing at least one pointer to the location in the *data storage space* of another said *cell* of said type; and
- *a field* which stores as one or more pointers the location within the *data storage space* of at least one of: (i) one of said *cells* of said type which is at least as large as any other of said *cells* and of said type, or (ii) one of said *cells* of said type which is at least as small as any other of said *cells* and of said type;

- said pointers being such that, starting from a *cell* of which the location is indicated in said *field*, any other of said *cells* can be reached by moving successively from one *cell* to another according to the pointers in a path in which the *size* of the *cells* varies monotonically.

By "monotonically" is meant that the *size* of the *cells* in the path either (i) never falls (e.g. in the case of starting with MINP), or (ii) never rises (e.g. in the case of starting with MAXP).

For example, at least one *cell* of each *size* may contain a pointer to a first one of the *cells* of the next higher (or lower) second *cell size*, and the pointers within the *cells* of the second *size* may define a path from the first *cell* through all the other *cells* of the second *size* to the *cell* of the second *size* which contains a pointer to a *cell* of the next higher (or lower) *cell size*.

Preferably, as in the first aspect of the current invention, the *cell* types are predetermined, but alternatively it would be possible for them to vary (e.g. be regularly reset) as part of an optimisation of the data structure in relation to the *computational task* in which it is employed.

The invention is defined above in terms of data structures. However, in third and fourth aspects, the invention in general terms respectively proposes using a data structure according to the first aspect or second aspect of the invention in a memory management method. The data structure may have any of the preferable features described in detail above in relation to the first aspect or second aspect of the invention.

Specifically, in the third aspect the invention provides a memory management method for controlling one or more *data storage devices* which support a *data storage space,* the memory management method including:

- deriving a first *data array* which, for each of one or more *cell sizes,* stores data indicating whether or not the *data storage space* includes at least one *free cell* of the respective *size;*
- deriving a second *data array* which, for any said *size* for which at least one *free cell* exists, indicates a location of at least one *free cell* of that *size* within the *data storage space;* and
- upon receiving an instruction to store a *data item,* determining using said first *data array* an appropriate *cell size* of a *free cell* for storing the *data item,* and using said second *data array* to derive the location within the *data storage space* of a location of *afree cell* of the determined *cell size.*

Preferably, the *data item* will be stored in the said *free cell,* the said *cell* will be converted into a *live cell,* and the first and second *data arrays* will be updated to indicate that said *cell* is no longer *free.*

Preferably, upon receiving an instruction to add a new *free cell* of a certain *size,* the location of said *cell* will be added to the appropriate *field* in the second *data array,* said *cell* will be converted to *a free cell,* and the *related fields* of the first *data array* will be updated to indicate that *a free cell* of said *size* exists.

No limitation is implied on the ordering of the operations in this method: operations may be ordered

sequentially or non-sequentially except where constrained by logical dependencies. :

In a fourth aspect the invention provides a memory management method for controlling one or more *data storage devices* which support a *data storage space*, the *data storage space* containing:

- one or more *free cells*, each said *cell* containing at least one pointer to the location in the *data storage space* of another said *cell;* and
- a *field* which stores the location within the data space of at least one of: (i) one of said *cells* which is at least as large as any other of said *cells*, or (ii) one of said *cells* which is at least as small as any other of said *cells;*
- said pointers being such that, starting from a *cell* of which the location is indicated in said *field*, any other of said *cells* can be reached by moving successively from one *cell* to another according to the pointers in a path in which the *size* of the *cells* varies monotonically;
- the method including identifying *a free cell* of a certain *size* by starting from a first *free cell*, and moving successively from one *cell* to another according to the pointers until a *cell* of that *size* is reached.

Preferably, upon receiving an instruction to store a *data item* of a certain *size*, an appropriate *free cell* will be determined using the method described in the fourth aspect and starting the search from the said *field*, the *data item* will be stored in the said *free cell*, the said free *cell* will be converted into a *live cell*, and the *cell* will be detached from the linked- list *of free cells*.

Preferably, upon receiving an instruction to add a new *free cell* of a certain *size,* said *cell* will be converted to *a free cell* and added to the linked-list *of free cells* in the appropriate position such that the properties expressed in the fourth aspect are maintained (i.e. the pointers provide a path in which the *size* of the *cells* varies monotonically).

No limitation is implied on the ordering of the operations in this method: operations may be ordered sequentially or non-sequentially except where constrained by logical dependencies.

Preferably, the first and fourth aspects of the invention will be combined so that, upon receiving an instruction to add a new *free cell* of a certain *size,* or to allocate a *data item* of a certain *size,* the appropriate position for adding the new *free cell* to or deleting an existing *free cell* from the linked-list *of free cells* may be determined by inspecting the first and second *data arrays* and said *data arrays* will be updated accordingly to indicate either the presence of a new *free cell* or that an *existing free cell* has been deleted. This has the effect that both adding a new *free cell* and allocating an *existing free cell* can be achieved in O (logp(MAXFIELDS)) time.

In both the third and the fourth aspects of the invention, the memory management method preferably further includes a step of identifying at least one *cell* of a type other than a *free cell* (e.g. a *live cell* or a *zombie cell)* and converting it into *a free cell.* Preferably, when a said *cell* is converted into *a free cell,* and if the *reference data* required for *a free cell* exceeds the available fields for *reference data* in the said *cell,* then *the fields* of the said *cell* that were used for *non-reference data* may be used to store the

reference data for the *free cell* after conversion. Preferably also, when *a free cell* is converted to a *live cell* as the result of allocation, those *fields* in the *free cell* that were used for *reference data* may be used for non- *reference data*.

For this purpose the memory management method preferably employs a data structure according to the first or second aspect of the invention in relation to *cells* of this other type.

In a fifth aspect, the invention proposes a memory management method for controlling one more *data storage devices* which support a *data storage space* containing one or more *zombie cells*, each *zombie cell* containing at least one pointer to the location in the *data storage space* of another *zombie cell*;

- the method employing *afield* which stores the location within the; data storage space of one of said *zombie cells* which is at least as large (or as small) as any other of said *zombie cells*;
- said pointers being such that, starting from a *zombie cell* of which the location is indicated in said *field*, any other of said *zombie cells* can be reached by moving successively from one *zombie cell* to another according to the pointers in a path in which the *size* of the *zombie cells* varies monotonically;
- the method including freeing *zombie cells* in an order defined by starting from a first *zombie cell*, and moving successively from one *zombie cell* to another according to the pointers.

Preferably, upon receiving an instruction to free a *zombie cell*, an appropriate *zombie cell* will be determined using the method described in the fifth aspect and starting the search from the *said field*, the said

zombie cell will be converted into *a free cell*, and *said free cell* will be detached from the linked-list of *zombie cells*.

Preferably, upon receiving an instruction to add a new *zombie cell* of a certain *size*, said *cell* will be converted to a *zombie cell* and added to the linked-list of *zombie cells* in the appropriate position such that the properties expressed in the fifth aspect are maintained (i.e. the pointers provide a path in which the *size* of the *cells* varies monotonically).

No limitation is implied on the ordering of the operations in this method: operations may be ordered sequentially or non-sequentially except where constrained by logical dependencies.

Preferably, the first and fifth aspects of the invention will be combined so that, upon receiving an instruction to add a new *zombie cell* of a certain *size*, or upon receiving an instruction to free a *zombie cell*, in the former case the appropriate position for adding the new *zombie cell* to the linked-list of *zombie cells* may be determined by inspecting the first and second *data arrays* and in both cases said *data arrays* will be updated accordingly to indicate respectively either the presence of a new *zombie cell* or the deletion of a *zombie cell*. This has the effect that adding a new *zombie cell* or freeing the largest *zombie cell* can be achieved in O(logp(MAXFIELD)) time.

In a sixth aspect, the invention proposes that the concepts described above are generalised by replacing cell size with any integer-valued property associated with a cell.

Specifically, in this a sixth aspect, the invention proposes a memory management method for controlling one

more *data storage devices* which support a *data storage space* containing one or more *cells*, each *cell* containing at least one pointer to the location in the *data storage space* of another *cell*, and each *cell* additionally associated with (e.g. containing) at least one integer quantity or property (which we call the *"sort value"*);

- the method employing *afield* which stores the location within the data storage space of one of said *cells* which contains a *sort value* that is at least as large (or at least as small) as any other *sort value* of said *cells*;
- said pointers being such that, starting from a *cell* of which the location is indicated in said *field*, any other of said *cells* can be reached by moving successively from one *cell* to another according to the pointers in a path in which the *sort value* of the *cells* varies monotonically;
- the method including deleting *cells* in an order defined by starting from a first *cell* and moving successively from one *cell* to another according to the pointers.

Preferably, upon receiving an instruction to delete a *cell*, an appropriate *cell* will be determined using the method described in the sixth aspect and starting the search from the *said field*, and the said *cell* will be detached from the linked-list of *cells*.

Preferably, upon receiving an instruction to add a new *cell* of a certain *sort value*, said *cell* will be added to the linked-list of *cells* in the appropriate position such that the properties expressed in the sixth aspect are maintained (i.e. the pointers provide a path in which the *sort value* of the *cells* varies monotonically).

No limitation is implied on the ordering of the operations in this method: operations may be ordered

sequentially or non-sequentially except where constrained by logical dependencies.

Preferably, the first and sixth aspects of the invention will be combined so that, upon receiving an instruction to add a new *cell* of a certain *sort value*, or upon receiving an instruction to delete a *cell*, in the former case the appropriate position for adding the new *cell* to the linked-list of *cells* may be determined by inspecting the first and second *data arrays* and in both cases said *data arrays* will be updated accordingly to indicate respectively either the presence of a new *cell* or the deletion of a *cell*. This has the effect that adding a new *cell* or deleting the cell with the largest *sort value* can be achieved in O(logp(MA.XFIELDS)) time.

The above defined sixth aspect of the current invention thus provides a "priority queuing" mechanism for sorting *data items* of a certain type with respect to any integer quantity or property of said *data items* or of the *cells* that contain said *data items*. A "priority queue" is a data structure and associated methods which support the insertion of *data items* in any order and the selection (i.e. deletion) of *data items* in a predetermined order (for example, in order of the *size* of the *cells* that contain said *data items*, or in order of the value of the *data item*, which mayor may not be numerical). Thus, it is a mechanism for sorting *data items* into a certain order. Priority queues are important for a wide range of computational tasks: for example, the scheduling of processes by an operating system, the routing of prioritised data in a communications network (for example, the Internet), the servicing of prioritised requests by an Object Request Broker, and the processing of data from multiple sensors (such as found, for example, in aircraft, spacecraft and self-navigating

missiles). When said computational task has real-time constraints, the time performance of the priority queue is a critical element of the successful implementation of that task.

Priority queues typically exhibit insertion and deletion time overheads that either both scale logarithmically with the number of *cells* in the queue, or one scales linearly with the number of *cells* in the queue and the other takes constant time. By contrast, the sixth aspect of the current invention provides a priority queuing mechanism that has deletion and insertion time overheads that scale as follows:

- where MAXFIELDS and MINFIELDS limits are set, O(logp (MAXFIELDS - MINFIELDS));
- where no limit is set, and the data arrays are not dynamically re-balanced, O(logp(maximum *cell* value));
- where no limits are set, and the data arrays are dynamically re-balanced, O(logp(number of different cell values)).

This has the effect that insertion and selection may be much faster than conventional priority queues in situations where there are many duplicates and where the values are clustered.

A further useful property of the current invention is that it allows data items of equal value (in terms of the criterion for selection) to be selected in order of age (either oldest-first or youngest-first). Most implementations of priority queues do not provide this facility. This has the effect that stronger guarantees can be provided about the behaviour of computer software that uses the current invention as the basis for priority queuing.

In further aspects the invention provides memory management methods (fully combinable with the methods according to any of the third to sixth aspects of the invention) in which a data structure according to the first or second aspect of the invention is updated by the insertion into it of a cell of the certain type, and the first and second tables and any pointers are updated accordingly. Preferably, this insertion preserves any information about the cells encoded by the pointers.

In further aspects, the invention provides a *data storage device* which is arranged to store a data structure according to the first and/or second aspects of the invention, and/or to perform any of the methods according to the invention (including means for performing each respective step of the methods). The invention further provides a computer system for performing a *computational task* and including such a *data storage device*.

Any of the above aspects may be fully combined, as demonstrated in two examples of the invention that will now be described in detail for the purpose of example only.

Detailed Description of two examples of the invention

The first example describes a priority queue that does not limit the sizes of the first and second data arrays (i.e. there is no MAXFIELDS limit). The second example describes a memory allocation system where the sizes of the first and second arrays are limited by MAXFIELDS.

Priority Queue

In this example the first and second *data arrays* of the first aspect of the current invention are merged for ease of implementation. The result is a single *data array* that contains both those *fields* determining the existence of *cells* of a certain value and those *fields* determining the location of said *cells* if they exist.

The *data array* comprises a hierarchy of memory "blocks". Each block consists of a bitmap (in this example, an unsigned 32-bit integer) and one or more *fields* held in contiguous locations (so that standard array indexing may be used to locate *afield* in constant time), with *each field* containing a pointer (in this example each block contains 32 pointers). At the lowest level, the pointers give the locations of cells: at all other levels the pointers hold the addresses of blocks in the next lower level. Additionally the *data array* contains *afield* holding a pointer to the top layer of the hierarchy, and *afield* that stores the current number of layers in the hierarchy. The bitmaps provide the implementation of the first *data array* of the first aspect of the current invention and the pointers provide the implementation of the second *data array* of the first aspect of the current invention.

Initially there exists a *sentinel cell* that had a known fixed address and is never subsequently moved or deleted. Each *cell* contains reference data including (i) the value of said cell to be used for ordering subsequent selection, and (ii) a pointer to the "next" *cell* of lower or equal value (if such a *cell* does not exist, this *field* is empty), and (iii) a pointer to the "previous" *cell* of higher or equal value (if such a *cell* does not exist, the pointer gives the location of the *sentinel cell).* Thus, the *cells* are arranged as a double-linked list. The double- linked list is at all times maintained in

monotonic order of *cell* value. This arrangement provides the implementation of the second aspect of the current invention.

To provide an implementation of a priority queue, the first and second aspects of the current invention are combined as follows. The pointers of the lowest level of the *data array* point to *cells* in this list -there is a single pointer from the *data array* for each different value that is currently being used for sequencing in the priority queue. For a certain value, if duplicate *cells* with that value exist, they are grouped next to each other in the double-linked
list and the pointer from the *data array* for that value gives the location of the cell which is linked to the *cell* with the next highest value (or to the *sentinel cell,* if no higher valued *cell* exists). This is illustrated in Figure 2.

The priority queue is initialised as follows:

- The *sentinel cell* is empty and there are no other *cells;*
- The *data array* has one block containing *32 fields* and a bitmap, each *field* being NULL and each bit in the bitmap being 0;
- The pointer to the top layer of the data array (we call this variable "top") contains the location of the first *field* (that which points to the *sentinel cell);*
- The variable which gives the number of layers in the *data array* (we call this variable "layers") is set to the value 1;
- Upon receipt of an instruction to insert a new cell into the priority queue, the following actions occur:

- The *reference data* of said *cell* is inspected to determine the value that will be used for subsequent selection -we call this value "x", We call said *cell* "this cell" and its previous and next pointers are called "previous" and "next",
- First we determine whether the *data array* has sufficient layers to support the insertion, If not, we create new layers:

```
while (x >= (32^layers)){
    ptr = new (block) ;      /*initialised empty */
        ptr[0] = top;
        top = ptr;
        layers = layers + 1;
        }
```

- Next, the following code performs an O(log N) search of the *data array*, where N is the largest value of any cell in the priority queue. If blocks are missing from the hierarchy, they are created.

```
        a = top;
                b = layers;
    While (b > 1)
            c = x div (32^(b-1)) -(32^(b-1)) *(x div
        (32^b));
            if (a[c] == NULL) {

            ptr = new (block) ; /*initialised with
        NULLs */
            a[c] = ptr;
            }
            a = a [c] ;
            b = b -1;
            }
            result = a[x mod 32] ;
```

- If the result is not empty (the pointer is not NULL) then simply de-reference the pointer to find the cell and link the new cell into the double-linked list of cells (the previous "result" pointer should be updated to point to the new cell). Otherwise update the "result" pointer to point to the new cell and undertake a search of the bitmaps in the *data array* to determine the previous and next cells in the double linked-list to which the new cell should be linked, and to set the appropriate bits in the related bitmaps to indicate the existence of the new cell (this procedure is explained in the second example, below, which considers a memory allocation system).

Upon receipt of an instruction to select (delete) the largest valued cell, this is achieved in O(log N) time (as with insertion) by (i) following the sentinel cell pointer to find the largest cell, (ii) detaching the largest cell by adjusting the sentinel pointer and the "previous" pointer in the next cell as necessary, (iii) traversing the data array from the top layer to the lowest layer to update the appropriate bits in the related bitmaps, and (iv) having reached the lowest level, updating the pointer in the data array (either to set it to NULL or to set it to point to the next cell of the same value as the cell just deleted).

Memory Management Method

This example of the invention is a memory allocation system where the sizes of the first and second arrays are limited by MAXFIELDS.

The memory allocation system provides best-fit memory allocation with allocation delays that are independent of the size of the memory.

The memory is divided into blocks. Each block comprises both an administrative data area and a user data area. If the block is not being used by the program (known as a "free" block), the user data held in the user data area is irrelevant and the user data area may therefore be used to hold additional administrative data. If the block is being used by the program (known as a "live" block) then the user data area may not be used for administrative data.

The administrative data for all blocks is the same and comprises:

(i) the size (the number of bytes) of the user data area

(ii) whether the block is free or live

(iii) whether the previous block (the block occupying an adjoining position in memory at a lower memory address) is free or live

(iv) the size (the number of bytes) of the user data area of the previous block

The sizes are expressed as numbers of bytes. The size of the user data area for a live block may not exceed MAXFIELDS bytes. The size of a free block may, however, exceed MAXFIELD bytes (as described below).

When the system starts, the memory contains amongst other things a single very large free block that represents the entire memory that the program may use. The size of this

block (to which we give the name "wilderness block") will be bigger than MAXFIELDS. Also, during the course of the program run, adjacent free blocks may be coalesced, and may thereby create a free block whose size is bigger than MAXFIELDS (we also give these the name "wilderness blocks").

This example describes a memory management system where MAXFIELDS is less than 32,768 and therefore both the availability (free or live) and the size of a block can be expressed with a 16 bit signed integer. The sign bit indicates whether the block is free (negative) or live (positive) and the magnitude indicates the size. An integer value of -32,768 indicates a free block that is bigger than 32,767 bytes and the actual size of the free block is stored in the data area of that block (see below).

Each free block contains, in addition to the required administrative data of two 16-bit integers (one for size and availability of this block, and one for the size and availability of the previous block), two pointers to other free blocks. The first such pointer (to which we give the name "leftp") gives the memory address of the free block that is next highest in a double-linked chain of free blocks. The second such pointer (to which we give the name "rightp") gives the memory address of the free block that is next lowest in the double-linked chain of free blocks. These two pointers are held at the start of the user data area of a free block. Each pointer requires 4 bytes and so the user data area of a block in this system must always be at least 8 bytes. If the program requests a block of less than 8 bytes user data area, it will be provided with a block of 8 bytes user data area (a request for a negative size is treated as an

error). This introduces a small amount of internal fragmentation. Wilderness blocks hold the actual size of the user data area in the user data area itself, immediately after the "rightp" pointer. A copy of the size is also held at the very end of the user data area (to assist coalescing of free blocks).

In summary, the three types of block have the following layout:

1. live block

administrative data area:
2 bytes - size and availability of this block - must be positive
2 bytes - size and availability of previous block
user data area:
N bytes - user data area, where N >= 8

2. free block (not wilderness)

administrative data area:
2 bytes - size and availability of this block - must be negative
2 bytes - size and availability of previous block
user data area:
4 bytes - "leftp" - memory address of next block in free list
4 bytes - "rightp" - memory address of previous block in free list
N bytes - user data area, where N >= 0

3. wilderness block (free)

administrative data area:

2 bytes - size and availability of this block - must be -32,768

2 bytes - size and availability of previous block

user data area:

4 bytes - "leftp" - memory address of next block in free list

4 bytes - "rightp" - memory address of previous block in free list

4 bytes - actual size of user data area

N bytes - remainder of user data area - where N >= 32,752

4 bytes - actual size of user data area

At initialisation, the memory comprises three blocks:

- a "sentinel" block (a live block used by the system) at the lowest address
- a "max" block (a live block used by the system)
- a "wilderness" block (available to the program)

The system also maintains:

(i) an array (to which we give the name "pgarray") of MAXFIELDS+1 pointers to free blocks that are not wilderness blocks. For administrative purposes the first pointer in this array (corresponding to a free block of size zero, which cannot exist) is initialised to contain the memory address of the "sentinel" block.

(ii) a pointer to the "max" block (which may, but need not, be held in the array described in (i), since entries 1-7 of that array will be unused)

(iii)a 3-level hierarchy of bitmaps containing information about the data held in the array described in (i). There need only be three levels if MAXFIELDS is

less than 32,768. The first level of bitmaps is an array (to which we give the name bitmap0) of 1024 unsigned integers. This will support up to 32768 entries in pgarray. The second level of bitmaps is an array (to which we give the name bitmap1) of 32 unsigned integers; this will support up to 1024 entries in bitmap0. The final level of bitmaps is a single unsigned integer to which we give the name bitmap2; this supports up to 32 entries in bitmap1.

(iv) a linked-list of free blocks in size order, with the lowest block in this linked list being the "sentinel" block and the highest block in this linked list being the "max" block. Note that the "sentinel" and "max" blocks are both live blocks, yet they are the two ends of the double-linked free-list. It is important that they are live, not free (unlike all other blocks on the free list) because they must never be allocated and they must never be coalesced with other blocks.

If this memory management system is to be used for a program that allocates only individual bytes of data, then fragmentation may be minimised by permitting the system to allocate blocks starting at any address in memory. However, if the program allocates larger units of data such as integers then additional internal fragmentation will occur because the system will be required only to allocate blocks where the user data starts at a memory address that is a multiple of 4 (alternatively, 8-byte or 16-byte alignment may be required); to achieve this, it is necessary to ensure that (i) the initial wilderness block has a user data area that starts at a suitably aligned memory address and (ii) all subsequent requests for block allocation are rounded up to the nearest size such that the neighbouring

free block (at higher address) has a user data area that is correctly aligned.

The method proceeds as follows:

1. an initialisation method ensures that:
   - the bitmaps firstly have all bits set to zero
   - the bitmaps then have the first bit at each of the three levels set to 1 (this is because pgarray will be initialised with pgarray[0] containing the address of the sentinel block)
   - pgarray[0] is given the memory address of the sentinel block, which is defined to be at the lowest end of memory
   - the sentinel block followed by the max block are allocated at the lowest end of memory alternatively, the max block could be placed at the upper end of memory). The "previous size and availability" data held in the max block are set to the appropriate data for the sentinel block.
   - two variables with the names "sentinelp" and "maxp" are set to contain the addresses of the sentinel block and the max block
   - a wilderness block is created in memory immediately after the max block, occupying all of the rest of the available memory. Because it is a wilderness block, pgarray does not contain an entry for this block. However, the block must be linked into the double-linked free list. The "previous size and availability" data for the wilderness block are set to the appropriate values for the max block. The "size and availability" data for the wilderness block are set to -32,768.

- the leftp for the sentinel block and the rightp for the max block are both set to the memory address of the wilderness block
- the rightp of the sentinel block and the leftp of the max block are both set to zero
- the leftp of the wilderness block is set to the address of the max block, and the rightp of the wilderness block is set to the address of the sentinel block.
- the size of the wilderness block is stored in the wilderness bloc just after the rightp and a copy is stored at the end of the user data area of the wilderness block

2. A main method receives memory requests from the program and allocates memory appropriately. Three different requests may be received: "malloc", "realloc" and "free".

The first is a request for the allocation of new memory of a given size; the main method finds the free block that is closest to the given size and splits that block into two parts - the lower part has a user data area that is the size required by the program (subject to alignment constraints as indicated above) and its memory address is returned to the program, whilst the upper part is retained as a free block for future use. The third request is that a live block at a given address should no longer be considered as live - it is therefore linked into the free list so that it may be available for future use. The second request is that a live block should be resized (either to a greater or smaller size), with the data in the current block being retained - this may be achieved by growing or shrinking the existing live block, or by allocating a new block, copying the data, and

freeing the existing block. For each request, the main method passes control to a subsidiary method to deal with the request. The three subsidiary methods are given the names "ccmalloc", "ccrealloc" and "ccfree". These three methods are described in detail below.

3. The method "ccmalloc"

This method is provided with the size of user data area that is requested. The method allocates the best-fit free block, unlinks that free block from the double-linked chain of free blocks, resets the pgarray and bitmaps a necessary, updates the administrative data for the block to show that it is now a live block, and returns the memory address of the block. If the selected free block is larger than the requested size, the remainder of the block may be divided from the requested part and the remainder is then treated as a new free block and linked into the double-linked chain of free blocks and the pgarray and bitmaps are updated as appropriate.

When ccmalloc is called for the first time, there will be no entries in pgarray apart from the pgarray[0] entry that points to the sentinl block. The leftp pointer of the sentinel block points to the wilderness block, which can then be split to satisfy the request.

The method is described in detail as follows:

- first the requested size is set to 8 if it is less than 8
- if the size is greater than MAXFIELDS, the allocator terminates with an error

- if pgarray[size] is not empty then a free block of the requested size is available; this block is changed from being a free block to a live block by passing the memory address of the identified block as an argument (together with the requested size) to a method with the name "ccdelete" (this method is described below). The address of the block is then returned as the result of this method "ccmalloc"
- if pgarray[size] is empty then no free block of the requested size exists, and so a search must be made for the next biggest free block.
- control is passed to the method "search"; with the requested size passed as an argument.The "search" method is described below. It returns the index in the pgarray corresponding to the next smallest free block
- the leftp of the next smallest free block contains the memory address of the next biggest free block. This is the block that will be used to satisfy the request. We name this the "target" block
- if the target block is a wilderness block then we chose a new target block which is the wilderness block whose address is held in the rightp of the max block. This switch (together with appropriate actions when free blocks are coalesced) ensures that those wilderness blocks that are created by coalescing are chosen to fulfil allocation requests in preference to the wilderness block at the end of memory - this in turn reduces the overall memory requirements of the program.
    - the amount of memory to be taken from the wilderness block will be the requested size (the administrative data at the start of the wilderness block can be reused for the newly-allocated block

- the size of the remaining block will be the current size of the target block less the requested size less the size of the administrative data for the remaining block - we give this value the name "j"
- the administrative data for the remaining block is set such that the "previous availability and size" is positive and is the requested size
- the administrative data for the newly allocated block is set such that "my size an availability" is positive and is the requested size
- if the size of the remaining block is less than 32,768 then the administrative data for the remaining block is set such that "my size and availability" is negative and has the value given by "j"
- and the memory address of the remaining block is passed as an argument to the method "ccfree" if the size of the remaining block is greater than 32,767 then the

administrative data for the remaining block is set such that "my size and availability" is the value -32,768 and the real size given by "j" is stored just after the rightp for the remaining block and a copy of "j" is stored at the end of the user data area of the

remaining block; the leftp for the remaining block is set to be a copy of the leftp for the target block and the rightp for the remaining block is set to be a copy of the rightp for the target block.Next the leftp of the block whose memory address is contained in the rightp of the target block is set to be the memory address of the remaining block and the rightp of the block whose

memory address is held in the leftp of the target block is set to be the memory address of the remaining block the memory address of the newly allocated block is returned as the result of the "ccmalloc" method

- if the target block is not a wilderness block then the address of the target block is passed (together with the requested size) as an argument to the method "ccdelete"
- the memory address of the newly allocated block is returned as the result of the "ccmalloc" method

4. The method "ccrealloc"

This method resizes an already-allocated (live) block. It takes two arguments: the memory address of the block to be resized, and the new size that the block should have. It returns the address of the resultant block.

- if the memory address is 0, there is no block to resize and so ccrealloc simply passes control to the method ccmalloc(size) and returns whatever memory address is returned by ccmalloc
- if the size is zero, the live block must be freed and so ccrealloc simply passes control to the method ccfree(address) and then returns a memory address of zero.
- the size of the block at the given memory address (the "current" block) is inspected (give it the name "current size") and is used to calculate the memory address of the next highest adjacent block in memory.

- the size of the next highest adjacent block in memory is inspected (we give this the name "nextsize")
- if nextsize indicates that the next block is a wilderness block then the true next size is read from the user data area of the wilderness block
- nextsize is set to its absolute value (the sign bit is ignored)
- if current size is the same as size then no work need be done - the ccrealloc method terminates and returns the original memory address as its result
- if the requested size is greater than the current size AND the current block is not the highest block in memory AND the next highest block in memory is free AND the requested size is less than or equal to MAXFIELDS AND (nextsize + current size + the size of the administration data area) is greater than the requested size AND (nextsize + current size) is greater than (the requested size + the minimum size of the user data area (in this example 8)) THEN perform the following actions:
  - calculate (requested size - current size - size of administration data area) and give it the name "growsize"
  - if growsize is negative, set growsize to zero
  - calculate (current size + growsize + size of administration data area) and give it the name "newsize"
  - pass control to the method "ccdelete", passing it three arguments: (i) the memory address of the next highest block, (ii) growsize and (iii) the Boolean value TRUE (which indicates that a value

for growsize of less than 8 should not be treated as an error nor be rounded up to 8)

- if newsize is greater than MAXFIELDS then terminate with an error message
- update the administrative data area for the current block such that "my size and availability" is set to be newsize (which should be positive, because this remains a live block)
- update the administrative data area of the newly-formed next highest block in memory such that its "previous size and availability" is set to be newsize (which should be positive)
- terminate this method and return the memory address of the current block

- if the previous test failed, then it is not possible (or not necessary) simply to grow the current block into the next highest block, so either the block should be shrunk or a new block should be allocated of the required size and the live data in the user data area of the current block should be copied to the new location. In fact, the latter approach subsumes the former in terms of correctness (if not in terms of efficiency!) and so to simplify this example we shall always allocate and copy even in situations where the current block could have been shrunk:

  - pass control to the method ccmalloc, passing it the requested size as an argument. The memory address returned by ccmalloc is given the name "cp2"
  - loop N times, where N is the smaller of the requested size and the current size, each time around the loop copying a byte of user data from

the current block to the block at memory address cp2

- pass control to the method ccfree, passing the memory address of the current block as an argument terminate this method and return as a result the memory address cp2

5. The method "ccfree"

The method ccfree frees a block that is not currently linked into the double-linked chain of free blocks; it does this by linking the block into the double-linked chain of free blocks and updating the pgarray and bitmaps accordingly. It takes as an argument the memory address of a block to be freed. it does not return any result.

- the memory address passed to ccfree is the address of a block to which we shall give the name "current block"
- the "previous size and availability" for the current block is inspected and stored in a local variable with the name "prevsize" and the "my size and availability" of the current block is inspected and stored in a local variable with the name "thissize"
- if thissize is -32,768 then read the actual size of the block from the memory location just after rightp, store this actual value in a local variable with the name "size", and calculate the memory address of the next highest block by adding the value of size (plus the size of the administration data area) to the memory address of the current block and store this value in a local variable with the name "nextblock"
- if thissize is not -32,768 then calculate the memory address of the next highest block by adding the value of thissize (plus the size of the administration data

area) to the memory address of the current block and store this value in a local variable with the name nextblock"; also set the value of size to be the same as the value of thissize

- if prevsize is -32768 then read the actual size of the previous block from the 4 bytes just before the administration data area of the current block (these are the top 4 bytes of the user data area of the previous block) and calculate the memory address of the previous block by subtracting this actual size (together with the size of the administration data area) from the memory address of the current block and store this value in a local variable with the name "prevblock"
- if prevsize is negative but not -32,768, calculate the memory address of the previous block by adding prevsize to the memory address of the current block and then subtracting the size of the administration data area and store this value in a local variable with the name "prevblock"
- otherwise, prevsize must be positive, so calculate the memory address of the previous block by subtracting prevsize (plus the size of the administration data area) from the memory address for the current block and store this value in a local variable with the name "prevblock"
- inspect the "my size and availability" of the next highest block and store it in a local variable with the name "nextsize"

- if (thissize is negative) AND (thissize is not -32,768) then terminate the method with an error message (because the only free blocks that might not be already attached to the free list are wilderness blocks)

The ccfree method then determines whether the current block can be coalesced with the next block in memory and/or the previous block in memory (one or both are already free). First the next block is considered, and then the previous block.

- if nextsize is negative then merge this block with the next block by executing the following instructions:
  - if nextsize is NOT -32,768 then it is not a wilderness block and so execute the following instructions:
    - if (size - nextsize + size of administration data area) is greater than MAXFIELDS then the result of coalescing will be a wilderness block so execute the following instructions:
      - pass control to the ccdelete method, passing three arguments: (i) nextblock, (ii) nextsize, and (iii) the Boolean value FALSE
      - calculate the memory address of the block after the next block as (nextblock - nextsize + the size of the administration data area) and store it in a local variable with the name "nextnextblock"
      - update the administration data area of the current block such that "my size and availability" is set to -32,768
      - update the memory address just above rightp for the current block such that it contains the value (size - nextsize + size of administration data area)
      - update the memory address 4 bytes before the administrative data area of the block after the

next block, such that it contains the value (size - nextsize + size of administration data area)

- if the block after the next block exists (i.e. if it is a valid memory address) then update the administration data area of that block such that "previous size and availability" is set to be -32,768

- if (size - nextsize + size of administration data area) is NOT greater than MAXFIELDS then the result of coalescing will not be a wilderness block so execute the following instructions:
  - update size with new value (size - nextsize + size of administration data area)
  - update the administration data area of the current block with the value -size (NB it must be negative)
  - calculate the memory address of the block after the next block as (nextblock - nextsize + the size of the administration data area) and store it in a local variable with the name "nextnextblock"
  - pass control to the method ccdelete, passing it three arguments: (i) nextblock, (ii) the value -size, and (iii) the Boolean value FALSE
  - if the block after the next block exists (i.e. if it is a valid memory address) then update the administration data area of that block such that "previous size and availability" is set to be -size

- if nextsize IS -32,768 then it is a wilderness block and so execute the following instructions:

- get the actual size of the next block and store it in a local variable to which we give the name "bignextsize"
- pass control to the method ccdelete with three arguments: (i) nextblock, (ii) bignextsize, (iii) the Boolean value FALSE
- update the administration data area of the current block such that "my size and availability" is set to -32,768
- calculate the new size which is (size + bignextsize + the size of the administration data area) and update the local variable size to contain this new value
- store the new value size in the current block at the memory address just after rightp
- store the new value size in the memory address obtained by adding size to the memory address of the current block minus 4 bytes
- calculate the value (bignextsize + nextblock + the size of the administration data area) and store this in the local variable with the name "nextnextblock"

- update the local variable nextblock to have the value stored in the variable nextnextblock

The ccfree method next considers the possibility of merging with the previous block.

- if prevsize is negative then merge this block with the previous block by executing the following instructions:

- if prevsize is NOT -32,768 then the previous block is not a wilderness block and the following instructions should be executed:
- update the variable size so that it has a new value given by the calculation (size - prevsize + size of administration data area)
- pass control to the method ccdelete, passing the three arguments (i) prevblock, (ii) - prevsize, and (iii) the Boolean value FALSE
- set the current block to be the memory address of prevblock
- if size is greater than MAXFIELDS then the coalescing has created a wilderness block and the following instructions should be executed:
- update the administration data area of the current block such that "my size and availability" is set to -32,768
- save the value size at the memory address just after rightp in the user data area of the current block
- save the value size at the memory address given by the calculation (prevblock + size - 4)
- if nextblock is a valid memory address, update the administration data area of nextblock such that "previous size and availability" is set to -32,768

- if size is not greater than MAXFIELDS then update the administration data area of the current block such that "my size and availability" is set to the value -size; then (if nextblock is a valid memory address) update the administration data area of the next block such that "previous size and availability" is set to -size

- if prevsize IS -32,768 then the previous block is a wilderness block, so execute the following instructions:
  - read the data held in the memory address 4 bytes before the administration data area forthe current block and store this in a local variable with the name "bigprevsize"
  - store in the memory address just after rightp for the previous block the value given by the calculation (size + size of administration data area + bigprevsize)
  - store the value given by the calculation (size + size of administration data area + bigprevsize) into the memory address given by the calculation (prevblock + size + size of administration data area + bigprevsize - 4).
  - if nextblock is a valid memory address, update the administration data area of nextblock such that "previous size and availability" is set - 32,768
  - pass control to the method ccdelete with three arguments as follows: (i) prevblock, (ii) size + bigprevsize + size of administration data area, and (iii) the Boolean value FALSE
  - update the current block so that it refers to the memory address stored in prevblock

The ccfree method has at this stage finished all coalescing and subsequently adds the current block (possibly now coalesced) into the free list and pgarray.

- inspect the administrative data area of the current block and store the value of "my size and availability" into a local variable with the name "thissize"
- if thissize is -32,768 then the current block is a wilderness block and the following instructions should be executed:
    - the current block is inserted at the top of the double-linked chain of free blocks, pointed to directly by the max block. This is achieved by updating the leftp of the current block to contain the memory address of the max block, by updating the rightp of the current block to contain a copy of the value currently stored in the rightp of the max block, by updating the leftp of the block whose memory address is stored in the rightp of the max block so that it contains the memory address of the current block, and by updating the rightp of the max block so that it contains the memory address of the current block
    - the ccfree method then terminates and control passes to the method that called ccfree.

- if thissize is NOT -32,768 then the current block is not a wilderness block and the following instructions should be executed:
    - set thissize to be the absolute value of thissize (i.e. make it positive if it is negative)
    - if (thissize is less than or equal to MAXFIELDS) AND (pgarray[thissize] is not empty) then link the current block into the double-linked list of free blocks just above the block whose memory address is held in

pgarray[thissize], and make pgarray[thissize] hold the memory address of the current block.

This is done by executing the following instructions:

- store in the leftp of the current block the memory address currently stored in the leftp of the block whose memory address is stored in pgarray[thissize]
- store in the leftp of the block whose memory address is held in pgarray[thissize] the memory address of the current block
- find the block whose memory address is now stored in the leftp of the current block and in the rightp of that block store the memory address of the current block
- store in the rightp of the current block the memory address that is held in pgarray[thissize]
- Note that we do NOT make pgarray[thissize] point to the current block yet - this is done later

- if either (thissize is greater than MAXFIELDS) OR (pgarray[thissize] is empty)then it will be necessary to search for the correct place in the double-linked chain of free blocks in which to insert the current block. This is done by executing the following instructions:
  - pass control to the method "set_and_search_bitmap" with one argument passed, which is thissize; this method will return a number which is then stored in a local variable with the name "i"

- update the rightp for the current block so that it contains the memory address held in pgarray[i]
- update the leftp for the current block so that it contains the data in the leftp of the block whose memory address is held in pgaray[i]
- update the leftp of the block whose memory address is held in pgarray[i] so that it contains the memory address of the current block
- update the rightp of the block whose memory address is held in the leftp of the current block so that it contains the memory address of the current block

- Next update the administration data area of the current block so that "my size and availability" is -thissize
- If the next block is a valid memory address, update its administration data area such that "previous size and availability" is -thissize
- If thissize is less than or equal to MAXFIELDS, update the contents of pgarray[thissize] so that it contains the memory address of the current block

6. the subsidiary method "ccdelete"

The method ccdelete is used internally (by ccmalloc and ccfree) - it deletes (unlinks) a specified block from the double-linked chain of free blocks and removes any reference to that block from either the pgarray or the bitmaps. It will also manage the splitting of such a

deleted block if required, with the lower sub-sblock remaining deleted and the upper sub-block being reinserted back into the double-linked list of free blocks (and pgarray and bitmaps updated accordingly).

The method takes three arguments (i) the memory address of a block to be deleted, which will be stored in a local variable with the name "cp" (ii) the size of the block to be deleted, which will be stored in a local variable with the name "size" (if it is less than the actual size of the block, this indicates that a split is requested), and (iii) a Boolean value to indicate whether it is OK to split just a very small (< 8 bytes) block from the start of the given free block

- this will be stored in a local variable with the name "small_is_ok".
- inspect the administration data area of the block whose memory address is held in cp (we give this the name "current block") and store the "my size and availability" data into a new local variable with the name "mysize"
- if mysize is negative and mysize is not -32,768 then update mysize with the value -mysize
- if size is negative than update size with the value -size
- read the data held in rightp of the current block and save it in a new local variable with the name "rightblock"
- store the value held in rightblock into the rightp of the block whose memory address is held in the leftp of the current block
- read the value stored in the leftp of the current block and store it into the leftp of the block whose memory address is held in rightblock

- if (mysize is not -32,78) AND (pgarray[mysize] is equal to cp) then execute the following instructions:
  - if the "my size and availability" data in the administration data area of the block whose address is stored in rightblock is equal to -mysize then update pgarray[mysize] so thatit holds the memory address that is currently stored in rightblock
  - else update pgarray[mysize] to contain an empty address (i.e. the value zero) and then pass control to the method "clear_bitmap", with mysize as an argument (and, when the method clear_bitmap returns, continue executing the next instruction for this method)
- if mysize is not -32,768 then (i) update the administration data area of the current block such that "my size and availability" is set to the value mysize, and (ii) if the next highest block (given by the memory address cp + mysize + size of adminstration data area) is a valid memory address, update the "previous size and availability" data of the administration data area of the next block to be the value mysize
- if (size is less than 8) AND (small_is_ok is FALSE) then set size to be 8
- if mysize is -32,768 then read the actual size from the memory address just after rightp in the user data area of the current block and store it in a new local variable with name "bigmysize"
- else store the value currently held in mysize into a new local variable with name "bigmysize"

- if (bigmysize - size - the size of the administration data area) is less than 8 then update size to be the value held in bigmysize
- if size is bigger than bigmysize then terminate this method with an error message
- if bigmysize is bigger than size then execute the following instructions:
    - calculate (cp + size) and store the result in a new local variable with the name "cp2"
    - if ((bigmysize - size - the size of the administration data area) is greater than MAXFIELDS) then execute the following instructions:
        - update the administration data area of the block whose memory address is held in cp2 wuch that "my size.and availability" is set to the value -32,768
        - if (cp + bigmysize + size of the administration data area) is a valid memory address then update the administration data area of the block at that address such that "previous size and availability" is set to -32,768
        - store the value (bigmysize - size - the size of the administration data area) into the memory location given by (cp2 + 8 + size of administration data area)
        - store the value (bigmysize - size - the size of the administration data area) into the memory location given by (cp2 + bigmysize - 4)
    - else execute the following instructions:

- update the administration data area of the block whose memory address is held in cp2 wuch that "my size and availability" is set to the value (bigmysize - size - size of administration data area)
- if (cp + bigmysize + size of the administration data area) is a valid memory address then update the administration data area of the block at that address such that "previous size and availability" is set to (bigmysize - size - size of administration data area)
- update the administration data area of the block whose address is stored in cp2 such that "previous size and availability" is set to the value held in size
- update the administration darta area of the current block such that "my size and availability" is set to the value held in size
- pass control to the method "ccfree", with the memory address currently held in cp2 as an argument

- else if (cp + bigmysize + size of administration data area) is a valid memory address then execute the following instructions:
  - calculate (cp + bigmysize + size of data administration area) and store the result in a new local variable with name "nextblock"
  - if bigmysize is greater than MAXFIELDS then update the administration data area ofnextblock such that "previous size and availability" is set to -32,768

- else update the administration data area of nextblock such that "previous size and availability" is set to bigmysize

7. The subsidiary method "search"

This method takes a single argument "size" and searches the bitmaps to find the highest set bit that is less than the bit representing the pgarray index "size". It returns the appropriate index.

- if size is greater than MAXFIELDS set size to be MAXFIELDS
- calculate the integer result of dividing size by 32 and store this value in a local variable with the name "bitindex"
- calculate the remainder after dividing size by 32 and store this value in a local variable with the name "bitremainder"
- if bitremainder is zero execute the following instructions:
  - if bitindex is zero then terminate this method and return the value zero
  - if bitindex is not zero then update bitindex with the result of subtracting one from the existing value of bitindex and then update bitremainder so that it contains the value 32
- create a 32 bit integer with only the top bit set and all other bits being zero (i.e. 0x80000000) and store it in a local variable with name "msb"
- calculate the result of right-shifting msb (bitremainder-1) times and store the result in a local

variable with the name "mask". The value stored in msb should NOT be altered.

- store the value (bitremainder-1) in a local variable with the name "i"
- loop until i is no longer positive, executing the following instructions each time around the loop:
  - if the result of the bitwise AND of bitmap0[bitindex] with mask is not zero then terminate this method and return the value given by the calculation ((bitindex multiplied by 32) + i)
  - update mask to be the result of the existing value of mask left-shifted once
  - update i to contain (i - 1)
- calculate the integer result of dividing (bitindex - 1) by 32 and store this value in a local variable with the name "j"
- calculate the remainder after dividing (bitindex - 1) by 32 and store this value in a local variable with the name "searchtop"
- update mask to contain the result of right-shifting msb searchtop times (the value held in msb should not be altered)
- set a local variable "foundit" to be the Boolean value FALSE
- update i to contain the value currently held in searchtop
- loop until i is no longer positive, executing the following instructions each time around the loop:
  - if the result of the bitwise AND of bitmap1[j] with mask is not zero then update foundit to contain the Boolean value TRUE and store the

value currently held in j into a new local variable with name "bitindex2" and store the value currently held in i into a new local variable with the name bitindex1 and then break out of this loop and continue with the remaining instructions for this method

- update mask to be the result of the existing value of mask left-shifted once
- update i to contain (i - 1)

- if foundit contains the Boolean value FALSE then execute the following instructions:
  - update mask to contain the result of right-shifting msb a number of times that is given by the remainder after dividing (j-1) by 32
  - update i to contain the remainder after dividing (j-1) by 32
  - loop until i is no longer positive, executing the following instructions each time around the loop:
    - if the result of the bitwise AND of bitmap2[0] with mask is not zero, update foundit to contain the Boolean value TRUE and update bitindex2 to contain the value currently held in i and then break out of this loop and continue with the remaining instructions for this method
    - update mask to be the result of the existing value of mask left-shifted once
    - update i to contain (i - 1)
  - if foundit contains the Boolean value FALSE then there has been an internal error and the method should terminate with an error message

- update mask to contain the result of right-shifting msb 31 times. The value held in msb should not be altered.
- update foundit to contain the Boolean value FALSE
- update i to contain the value 31
- loop until i is no longer positive, executing the following instructions each time around the loop:
  - if the result of the bitwise AND of bitmap1[bitindex2] with mask is not zero then update foundit to contain the Boolean value TRUE and update bitindex1 with the value currently held in i and then break out of this loop and continue with the remaining instructions for this method
  - update mask to be the result of the existing value of mask left-shifted once
  - update i to contain (i - 1)
- if foundit contains the Boolean value FALSE then there has been an internal error and the method should terminate with an error message

- update mask to contain the result of right-shifting msb 31 times. The value held in msb shold not be altered.
- update foundit to contain the Boolean value FALSE
- update j to contain the value 31
- loop until j is no longer positive, executing the following instructions each time around the loop:
  - if the result of the bitwise AND of bitmap0[bitindex1 + (bitindex2 * 32)] with mask is not zero then update foundit to contain the Boolean value TRUE and update bitremainder with the value currently held in j and then break out of this loop

and continue with the remaining instructions for this method

- update mask to be the result of the existing value of mask left-shifted once
- update j to contain (j - 1)
- if foundit contains the Boolean value FALSE then there has been an internal error and the method should terminate with an error message
- terminate this method and return as the result the value obtained by the calculation (((bitindex1 + (ibtindex2 * 32)) * 32) + bitremainder)

8. The subsidiary method "clear_bitmap"

This method takes a single argument "size" and updates the bitmaps so that they reflect the fact that there is no valid memory address in pgarray[size]. There is no return value.

- create a 32 bit integer with only the top bit set and all other bits being zero (i.e. 0x80000000) and store it in a local variable with name "msb".
- calculate the integer value of (size / 32) and store the result in a local variable with the name "bitindex"
- calculate the remainder after size has been divided by 32 and store the result in a local variable with the name "bitremainder"
- update bitmap0[bitindex] with the result of calculating the bitwise AND of the current value stored in bitmap0[bitindex] and the result of (right-shifting msb bitremainder times and then inverting every bit). The value of msb should not be altered.
- if bitmap0[bitindex] is zero then :

- update bitremainder to be the remainder after bitindex has been divided by 32
- update bitindex to be the integer result of dividing the existing value held in bitindex by 32
- update bitmap1[bitindex] with the result of calculating the bitwise AND of the existing value of bitmap1[bitindex] with the result of (right-shifting msb bitremainder times and then inverting all the bits). The value of msb should not be altered.

- else:
  - update bitindex to be the integer result of dividing the existing value held in bitindex by 32
  - if bitmap1[bitindex] is zero then:
  - update bitremainder to be the remainder after bitindex has been divided by 32
  - update bitindex to be the integer result of dividing the existing value held in bitindex by 32
  - update bitmap2[bitindex] with the result of calculating the bitwise AND of the existing value of bitmap2[bitindex] with the result of (right-shifting msb bitremainder times and then inverting all the bits).

9. The subsidiary method "set_and_search_bitmap"
This method achieves two objectives: it updates the bitmaps to indicate that pgarray[size] contains a valid memory address, and it searches for the biggest set bit that represents a pgarray index less than size. It then returns the appropriate index.

- pass control to method "search", passing the argument size; the method "search" will return an integer that is then stored in a local variable with the name "i"
- if size is less than or equal to MAXFIELDS, then update the bitmaps as follows:
  - create a 32 bit integer with only the top bit set and all other bits being zero (i.e. 0x80000000) and store it in a local variable with name "msb"
  - calculate the integer value of (size / 32) and store it in a local variable with name "bitindex"
  - calculate the remainder after size is divided by 32 and store that remainder in a local variable with name "bitremainder"
  - update bitmap0[bitindex] with the result of calculating the bitwise OR of the existing value of bitmap0[bitindex] with the value obtained by right-shifting the value stored in msb bitremainder times (the value held in msb should NOT be altered)
  - update bitmap1[bitindex / 32] with the result of calculating the bitwise OR of the existing value of bitmap1[bitindex/32] with the value obtained by right-shifting msb by the number of times that is the result of calculating the remainder after dividing bitindex by 32 (the value held in msb should NOT be altered)
  - update bitmap2[(bitindex/32)/32] with the result of calculating the bitwise OR of the existing value of bitmap2[(bitindex/32)/32] with the value obtained by right-shifting msb by the number of times that is the result of calculating the remainder after (bitindex/32) is divided by 32

- terminate this method and return the value i

Claims

1. A data structure comprising:

a *data storage space;*

a first *data array* which, for each of one or *more-cell sizes,* stores data indicating whether or not the *data storage space* includes at least one *cell* of a certain type and of the respective *size;* and

a second *data array* which, for any said *size* for which at least one *cell* of the determined type exists, indicates a location of at least one *cell* of that *size* and type within the *data storage space.*

2. A data structure according to claim 1 in which said predetermined *cell sizes* are no more than a predetermined maximum cell size which is independent of the total *size* of the data storage space.

3. A data structure according to claim 2 in which said predetermined *cell sizes* are all *cell sizes* up to the predetermined maximum *cell size (MAX FIELDS).*

4. A data structure according to claim 3 in which the first *data array* is selected so that for a *cell size* n it is possible to determine the smallest (integer) value of p such that p>n and there exists at least one *cell* of the predetermined type of *size* p, within a time which scales with log (MAXFIELDS).

5. A data structure according to claim 3 in which the first *data array* is selected so that for a *cell size* n it is possible to determine the largest (integer) value of p

such that p<n and there exists at least one *cell* of the predetermined type of *size* p, within a time which scales with log (MAXFIELDS).

6. A data structure according to any preceding claim in which the first *data array* is a hierarchical *data array*, having:

a first level which includes one or more first *fields*, each first *field* indicating for a respective *size* of *cell* the existence or otherwise of at least one *cell* of that *size*, said first *fields* being divided into one or more groups, each group representing a respective range of *cell sizes*; and

a second level which includes one or more second *fields*, each second *field* indicating for a respective said group the existence or otherwise of at least one *cell* in the respective range of *cell sizes*.

7. A data structure according to claim 6 in which the first *data array* contains further layers above the second layer, there being in each i-th layer one or more *fields*, for each layer except the top layer, the one or more *fields* are divided into one or more groups, each group representing a range of *cell sizes*, and in the (i+ 1)-th layer there is a *field* for each respective group of the i-th layer.

8. A data structure according to claim 7 in which in each layer, each group represents a number *offields* in the layer below which is a multiple of eight.

9. A data structure according to any of claims 6 to 8 in which each of said fields of at least the first level indicates the existence or otherwise of at least one cell of said size or size range by a binary variable.

10. A data structure comprising:

a *data storage space;*

a first *data array* which, for each of one or more *cell size* ranges, stores data indicating whether or not the *data storage space* includes at least one *cell* of a certain type within the respective *size* range; and

a second *data array* which, for any of said *size* ranges for which at least one *cell* of the determined type exists, indicates a location of at least one of those *cells* within the *data storage space.*

11. A data structure according to any preceding claim which includes a *field* which stores the location of at least one of: (i) a *cell* of the predetermined type having the greatest *size* for which *cells* of the predetermined type exist, or (ii) a *cell* of the predetermined type having the smallest *size* for which *cells* of the predetermined type exist.

12. A data structure according to any preceding claim in which the *cells* contain pointers to each other such that, starting from any *cell* of any predetermined *cell size,* any other *cell* of the predetermined type and the same *cell size* can be reached by moving successively from one *cell* to another according to the pointers.

13. A data structure according to claim 12 in which at least one *cell* of each predetermined *size* contains a pointer to one of the *cells* of the next higher occupied predetermined *cell size,* and/or at least one *cell* of each predetermined *size* contains a pointer to one of the *cells* of the next lower occupied predetermined *size.*

14. A data structure according to claim 12 or claim 13 in which the order of the path defined by the pointers through *cells* of the same *size* encodes information about the *cells* of that *size*.

15. A data structure according to claim 12, claim 13 or claim 14 which includes at least one *cell* of the predetermined type which is of minimum *size*, has a predetermined location in the *data storage space* and contains a pointer to a *cell* of the predetermined type of the same or next higher *size*.

16. A data structure including:

a *data storage space*, the *data storage space* comprising one or more *cells* of a certain type, each said *cell* of said type containing at least one pointer to the location in the *data storage space* of another said *cell* of said type; and

a field which stores as one or more pointers the location within the *data storage space* of at least one of: (i) one of said *cells* of said type which is at least as large as any other of said *cells* and of said type, or (ii) one of said *cells* of said type which is at least as small as any other of said *cells* and of said type;

said pointers being such that, starting from a *cell* of which the location is indicated in said *field*, any other of said *cells* can be reached by moving successively from one *cell* to another according to the pointers in a path in which the *size* of the *cells* varies monotonically.

17. A memory management method for controlling one or more *data storage devices* which support a *data storage space,* the memory management method including:

deriving a first *data array* which, for each of one or more *cell sizes,* stores data indicating whether or not the *data storage space* includes at least one *free cell* of the respective *size;*

deriving a second *data array* which, for any said *size* for which at least one *free cell* exists, indicates a location of at least one *free cell* of that *size* within the *data storage space;* and

upon receiving an instruction to store a *data item,* determining using said first *data array* an appropriate *cell size* of a *free cell* for storing the *data item,* and using said second *data array* to derive the location within the *data storage space* of a location of a *free cell* of the determined *cell size.*

18. A memory management method for controlling one or more *data storage devices* which support a *data storage space,* the *data storage space* containing:

one or more *free cells,* each said *cell* containing at least one pointer to the location in the *data storage space* of another said *cell;* and

a *field* which stores the location within the data space of at least one of: (i) one of said *cells* which is at least as large as any other of said *cells,* or (ii) one of said *cells* which is at least as small as any other of said *cells;*

said pointers being such that, starting from a *cell* of which the location is indicated in said *field,* any other of said *cells* can be reached by moving successively from one *cell* to another according to

the pointers in a path in which the *size* of the *cells* varies monotonically;

the method including identifying a *free cell* of a certain *size* by starting from a first free cell, and moving successively from one *cell* to another according to the pointers until a *cell* of that *size* is reached.

19. A memory management method for controlling one more *data storage devices* which support a *data storage space* containing one or more *zombie cells*, each *zombie cell* containing at least one pointer to the location in the *data storage space* of another *zombie cell*;

the method employing *afield* which stores the location within the data storage space of one of said *zombie cells* which is at least as large, or at least as sl:llall, as any other of said *zombie cells*;

said pointers being such that, starting from a *zombie cell* of which the location is indicated in said *field*, any other of said *zombie cells* can be reached by moving successively from one *zombie cell* to another according to the pointers in a path in which the *size* of the *zombie cells* varies monotonically;

the method including freeing *zombie cells* in an order defined by starting from a first *zombie cell* and moving successively from one *zombie cell* to another according to the pointers.

20. A memory management method for controlling one more *data storage devices* which support a *data storage space* containing one or more *cells*, each *cell* containing at least one pointer to the location in the *data storage space* of another *cell*, and each *cell* additionally being associated with at least one integer property;

the method employing *afield* which stores the location within the data storage space of one of said

cells which contains a *value* of said property which is at least as large, or at least as small, as any other value of said property of said *cells;*

said pointers being such that, starting from a *cell* of which the location is indicated in said *field,* any other of said *cells* can be reached by moving successively from one *cell* to another according to the pointers in a path in which the value of said property of the *cells* varies monotonically;

the method including deleting *cells* in an order defined by starting from a first *cell,* and moving successively from one *cell* to another according to the pointers.

21. A *data storage device* which is arranged to store a data structure according to any of claims 1 to 16.

22. A data storage device which performs a method according to any of claims 17 to 20.

23. A computer system for performing a *computational task* comprising a *data storage device* according to claim 21 or 22.

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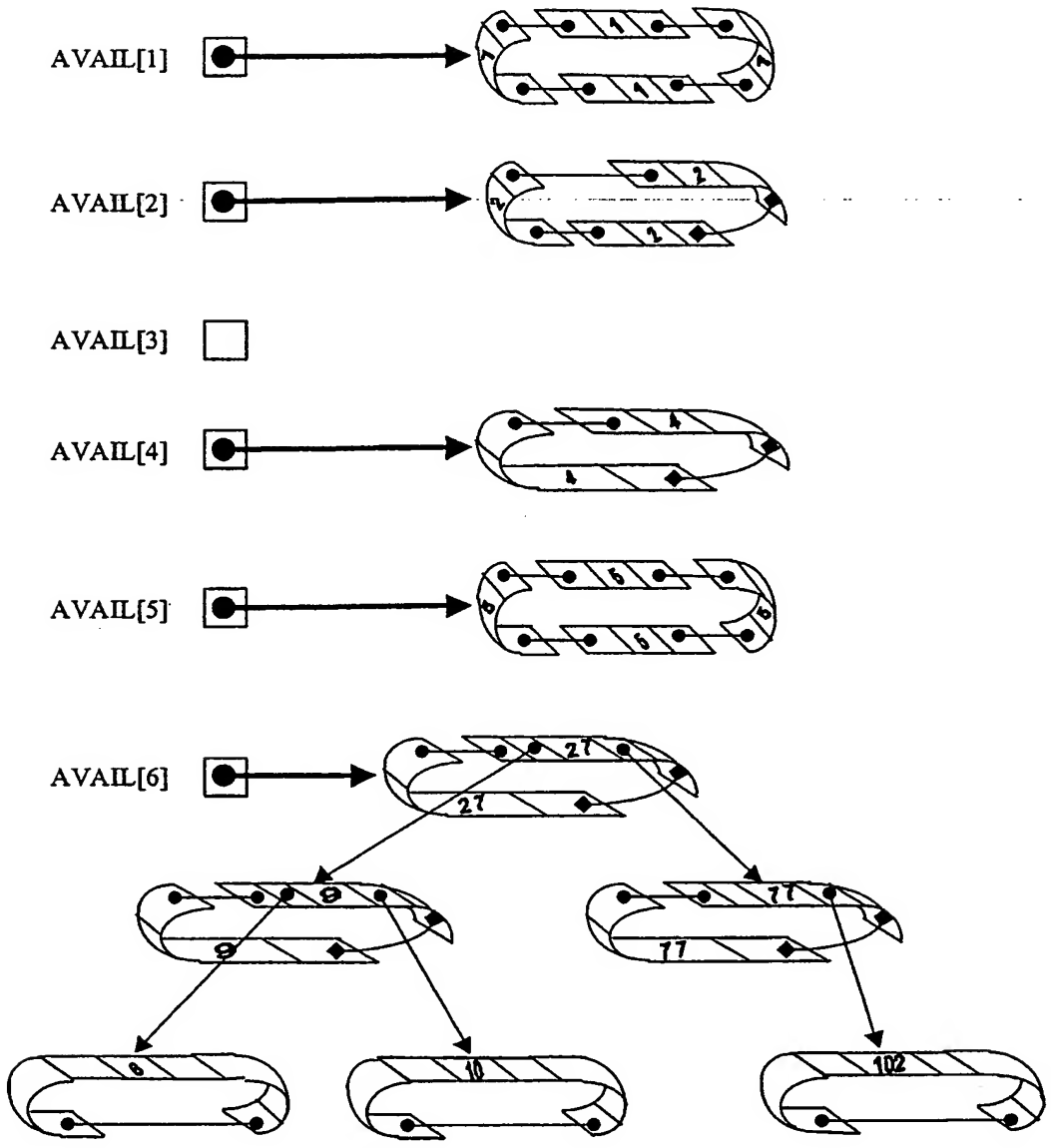
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Fig. 1

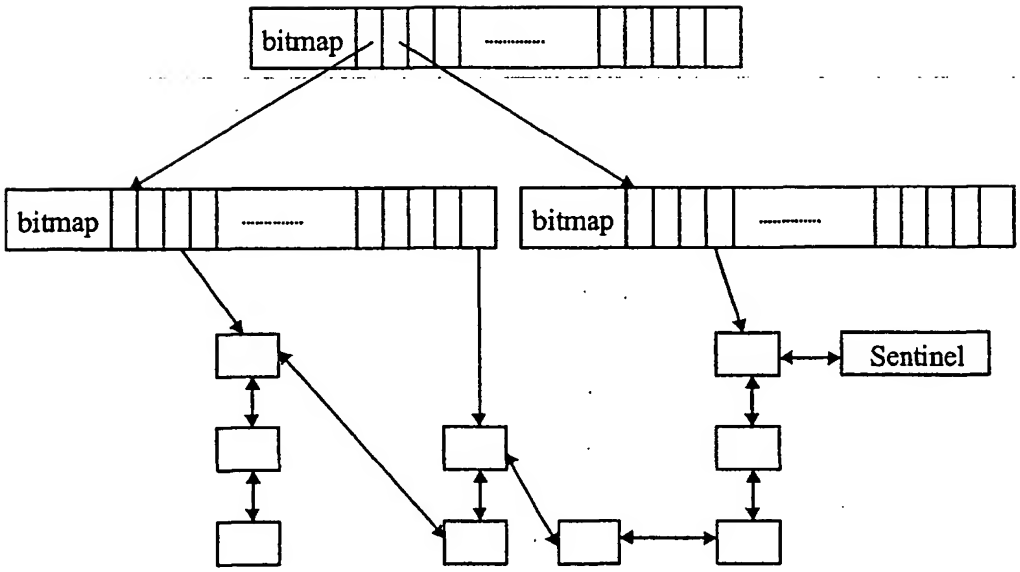

Figure 2

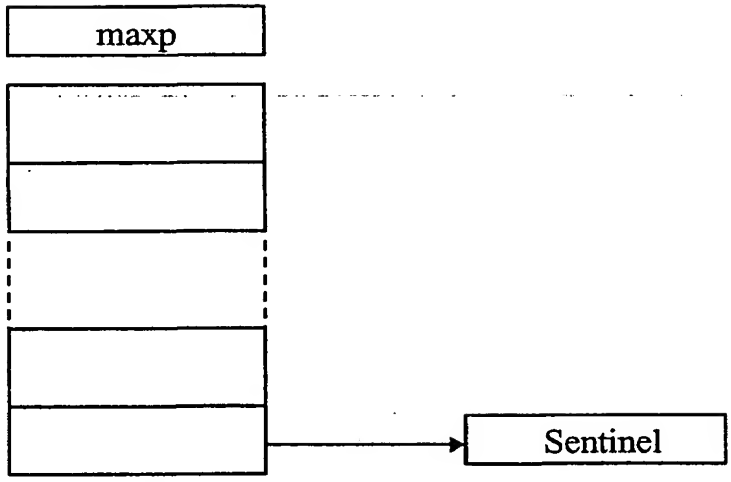

Figure 3 : Initial State of a Peer-Group List

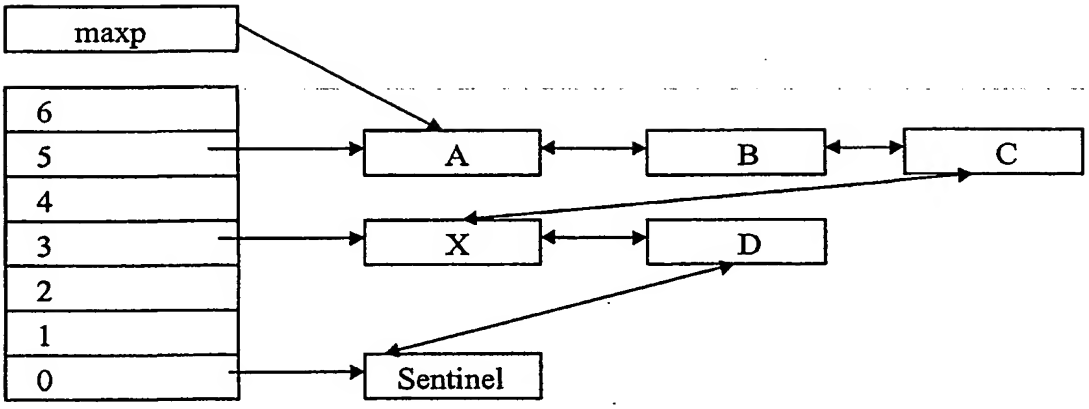

Figure 4 : Before Deletion of cell X

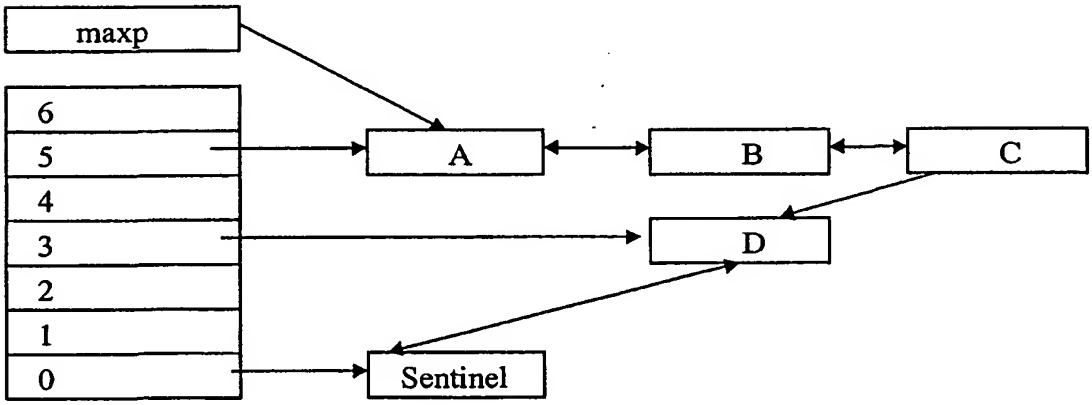

Figure 5 : After Deletion of cell X

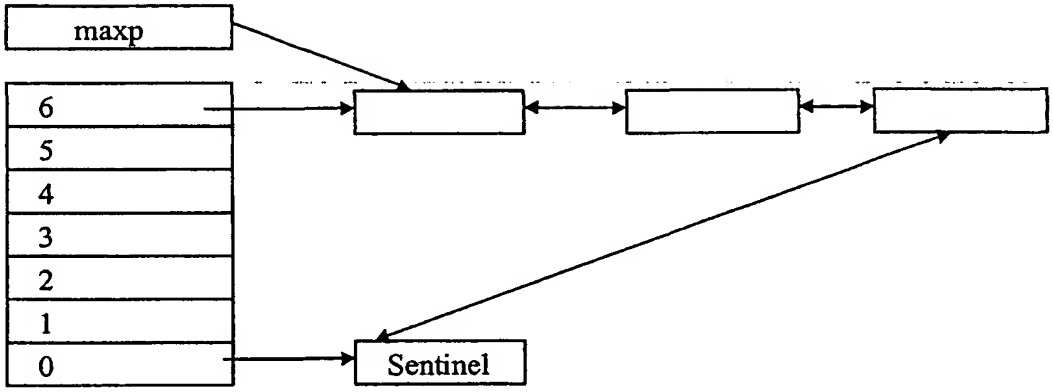

Figure 6 : Before Insertion of cell

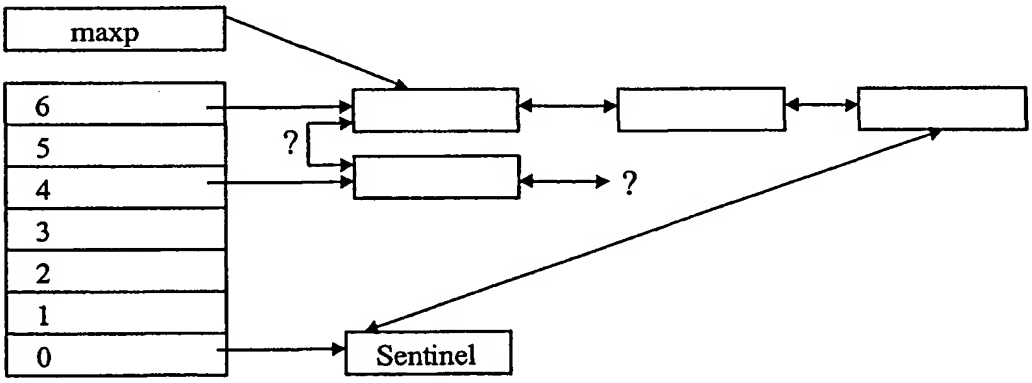

Figure 7 : A problem with Insertion

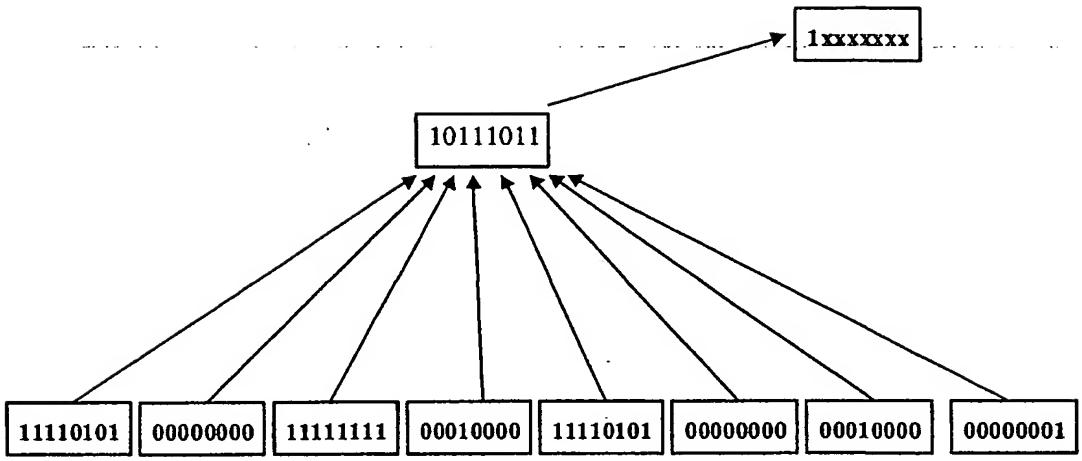

Figure 8 : Bitmap Abstractions

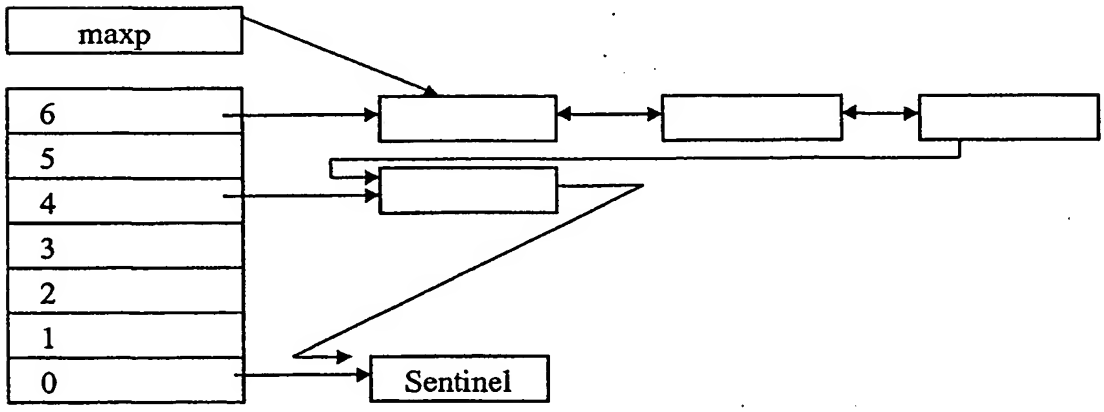

Figure 9 : Insertion problem resolved

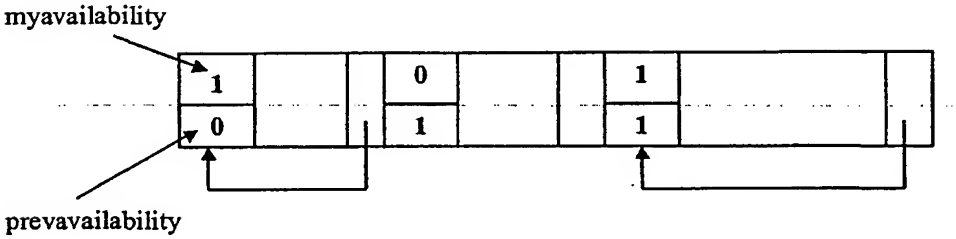

Figure 10 : Availability of Cells

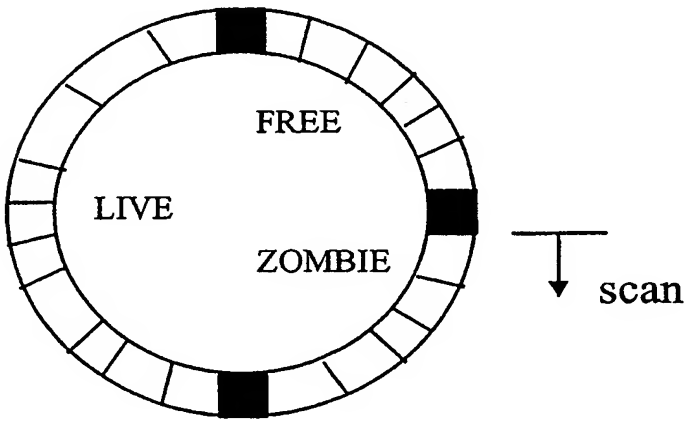

Figure 11: Treadmill Similarity